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HUMAN ENGINEERING

BY

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HUMAN ENGINEERING*

Consulting Editor and Conference Chairman
LAWRENCE EDWIN ABT

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A PROGRAM OF HUMAN ENGINEERING

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The program which I shall outline is not the ideal one which might be proposed to the world at large. Rather, it is the one being sponsored at the present time by the Special Devices Center of the Office of Naval Research. Like most programs, it came into being gradually in order to meet various needs, emergencies, requests, and other administrative necessities. This is not to say that we are not approaching a logically complete and rounded set of projects so that in time it might be possible to describe the program and to show how each paper in a monograph such as this is related to the whole. As will be pointed out later on, we have a scaffolding pretty well erected, but a great deal of construction still remains to be done.

Here is my plan of presentation: first, a few words of historical perspective to show the antecedents of the human engineering field; then, a definition of the topic and some related areas of endeavor; next, an outline of the program with which I am most familiar; and finally, an illustration of some results already obtained from human engineering research within the major parts of this outline.

Historical Perspective. Human engineering problems seem to arise whenever man is confronted with so-called technological advancements. I suppose the primitive cave dweller would have profited if his tools and weapons had been shaped and weighted so as to fit his psycho-physiological capacities. The need for such a state of affairs, in this instance, does not seem very pressing. It resembles the act of giving Aristotle a telephone. It was not until the machine age was well advanced, in the 19th century, that anyone did any systematic worrying about the fact that man was actually the weak link in mechanized production. The time-study work of Taylor in the eighties, followed by the motion-study contribution of the Gilbreths, represent the first organized attempts to make man a more efficient partner in the modern industrial scene.

During this same period, the notion was being developed in the new field of psychology that individuals were constituted differently and that some people might naturally be better suited for particular types of jobs. The mental testing movement got under way and led to the development of intelligence and aptitude tests. World War I gave both impetus and status to the personnel selection movement. Thus, during the early decades of the 20th century, we find both engineers and psychologists attempting to adapt human beings to the demands of a technological society.

Meanwhile, another group of scientists, the experimental psychologists, were developing their field by the discovery of new facts and techniques concerning man's sensory and perceptual processes. It was a long time before this group became enmeshed in the practical problems of matching

*The opinions or assertions contained herein are the private ones of the writer and are not to be construed as official or as reflecting the views of the Navy Department or the naval service at large.

man with the technical appurtenances of his civilization. In fact, the leading experimentalists took pride in divorcing themselves from the applied aspects of their research, and a number of psychological publications made the point that this type of psychology must remain "pure." It required the stress of World War II to bring this group of specialists into the human engineering field. Early in the war, it was discovered that the potentialities of modern weapons and equipment, despite their superior engineering achievements were not yielding the performance that their advanced design seemed to merit. It was recognized, too late in many instances, that the human operator remained an essential link in military tasks and procedures, and that special effort would be required to design the equipment so that it fitted the natural characteristics of the average man. It was the experimental psychologist who seemed to know most about these normal capabilities. What World War I did for the mental testing movement, World War II seems to have done for experimental psychology. In tracing the history of this movement, it is interesting to point out that engineers first invaded the domain of psychology by recommending certain behavioral procedures on the basis of their time and motion studies. We wind up this survey by finding that psychologists have encroached on the engineers by specifying the manner in which equipment should be designed.

Definition of Human Engineering. It should be fairly obvious by now what the writer considers human engineering to be. Our definition goes like this: Human engineering is that endeavor which seeks to match human beings with modern machines so that their combined output will be comfortable, safe, and more efficient. Obviously, this sort of effort belongs to no one professional group and requires the special aptitudes of many individuals. In addition to the engineers who devise a particular type of equipment, there may be the need, depending on the problem, for motion- and time-study men, physicians, psychologists, physiologists, and other specialists from the field of the biological sciences. Also, the problems of human engineering are of great diversity. Many industrial situations present particular environmental problems of heat, noise, lighting, humidity, noxious gases, and so forth. Modern aircraft, both commercial and military, repeat and add to this list of physical factors which may affect the human being adversely. Military equipment has confronted us with the necessity for the design of instrument indicators which are quickly interpretable without error, and conveniently arranged controls whose physical characteristics match our muscular capabilities. The design and use of prosthetic devices is another area which has brought the engineer, medical man, and psychologist together.

The examples of human engineering endeavor just cited seem to constitute a unique set of problems. Some individuals would prefer to call this general area "engineering psychology," a phrase which is perfectly acceptable to the writer. But we must draw the line somewhere. It is proposed, therefore, that we do not attempt to include in this field endeavors which are better called human relations, personnel management, or labor relations. I have heard the term "human engineering" applied to all three of these

fields during the past few months. There is no objection, naturally, to these types of activity. It is proposed, however, that the term "human engineering" will lose much of its value if it is applied indiscriminately to all attempts to fit the individual into his social and economic, as well as his mechanical, environment. Let us confine ourselves, therefore, to that area of scientific endeavor which seeks an optimal *rapprochement* between the individual and the mechanized tasks which he is required to perform in our society.

Some of my readers undoubtedly are of the opinion that this laboring over the matter of definition is merely a bit of definitional hair-splitting. However, as one of a very small number of people who are actually called human engineers, and as one who sincerely believes that the events of the past few years have produced a unique opportunity and need for the combined efforts of the engineering and biological professions, I am convinced that the recognition and delimitation of this biomechanical field is essential to its success.

A Program of Human Engineering. As previously mentioned, the writer does not profess to be in a position to present a final and idealized program of human engineering. Most of his experience has been concerned with military problems, and the general trends and outlines which are to be mentioned stem from this experience. It has become apparent, however, that there are parallel phenomena in industrial civilian life. The dual application of many of our military research results will be apparent.

Our definition of human engineering gave as its goal a man-machine combination which was efficient, comfortable, and safe. So far as efficiency is concerned, the objective is to arrange a given operation so that it is accurate, rapid, and without error. One way of eliminating human error is to automatize the operation and thereby eliminate the operating personnel. This commendable objective frequently backfires, however, by resulting in a situation in which some men are eliminated but in which the tasks for the remaining individuals become more complicated than ever. Meanwhile, our technology continues to produce machines, gadgets, equipment, and vehicles which require novel and difficult skills on the part of their users. Since man does not evolve as rapidly as engineering, it behooves us to persuade the engineer to design his contributions to allow for the natural capabilities of the normal individual.

Thus, the first plank in our human engineering platform is the acquisition of knowledge concerning man's natural capabilities and limitations. Although a great deal of this knowledge has already been provided by the biological sciences, most of it was not gathered with our present objectives in view. There is the need, therefore, for a careful review and analysis of psycho-physiological data already in existence in the professional journals, service and OSRD reports, so that those who are concerned with equipment design problems may be made aware of the knowledge which already has been gathered. Because of the interdisciplinary skills which human engineering engenders, this literature survey function is regarded as being of an almost equal importance as new research efforts. The paper by Dr. Ken-

nedy will present experiences and up-to-date results in attempts to fulfill this function.

The types of experimental studies which also are required in our ideal program may be grouped into the following areas:

(1) *Studies of the optimal environment.* By this term, we mean investigations which will specify the effects of physical factors having either a deleterious or favorable influence on operator behavior. Great progress has been made, in recent years, by the engineering profession on the manner in which temperature, humidity, and ventilation interact to affect worker output. Other variables which are encountered in industrial situations are noxious gases, noise (sonic and ultrasonic), vibration, and illumination. Commercial aviation has given us the additional complications of oxygen deficiency, air pressure, acceleration, and motion.[8] Military circumstances make it even more difficult to obviate the undesirable effects of these physical factors. Continued cooperation between members of the engineering, medical, and psychological sciences will be required so as to protect the individual while working in environments which offer hazards to his safety and efficiency.

(2) *Studies of equipment display.* This area has been under attack for an appreciable period of time, and many general principles are now available for application. As these data become more widely known, we can anticipate more functional designs of dials, scale, meters, graphs, and other types of instrument and tabular indicators. Included in this problem of the display of machine information are the layout and arrangement of the working place. It is easy to think of instances where a simple rearrangement or redesign of the machine indicators and layout would have greatly eased the sensory requirements of the job.

(3) *Studies of equipment controls.* This is an area which the psychological and medical science investigators have neglected too long. The information that exists has come from the engineering side of the ledger and is expressed in the general principles of motion and time study. The rules of motion economy have been appraised by the practical yardstick of greater and faster production. But is this the best criterion for making recommendations on man's motor performance? The old controversy as to whether there is "one best way" to perform an operation still needs to be resolved. It is pleasant to observe that cooperative efforts, begun during World War II, are now in progress on the physical design of machine controls. In the near future, we may expect definitive recommendations on the optimal size, shape, gearing, direction of motion, speed of motion, inertia, friction, and so forth, of different types of controls in various machine situations. This matter of control design is associated closely with the previously mentioned second category of our program: The specification of the ideal controls must be associated with the equipment display. An important item in this regard is the extent to which a control knob, wheel, or lever can serve as an instrument display. More data are needed on the extent to which the muscle sense can be utilized in task procedures.

(4) *Studies of man-machine systems.* This area is probably not of the great significance in civilian industrial situations that it is in military opera-

tions. In the latter case, we have a great many instances where large groups of men must coordinate their individual efforts so as to meet a single objective. What we have in mind here are the many instances of crew coordination as demanded in the control of vehicles such as ships and airplanes. Communication networks are another illustration where the human factor may determine whether a complex physical system will or will not function properly.

Let us summarize what has been stated in regard to our program of human engineering. The first requirement is the acquisition of knowledge which will specify what the normal working man can do naturally. It is proposed that this objective can be satisfied by the collection and dissemination of already existent facts, and by the conduct of further research on the working environment, equipment display, machine controls, and system studies. Such information can be found in the stockpile of knowledge possessed by the engineering profession and by the biological scientists. Without cooperative effort on the part of these groups, the solution to many present-day problems will remain one-sided or unsatisfactory.

While speaking of the requirement for interdisciplinary effort, there is need for a further detail of explanation. Dr. McFarland recently informed the writer of his experience during a meeting of engineers, physicians, and psychologists, who were discussing problems of aeronautics. The medical men and the psychologists described errors in cockpit design from the point of view of physical safety and ease of operation. To this, the engineers took offense and pointed out, justly, that they made their aeroplanes according to design specifications furnished by others. The point is that the engineers are not basically responsible for machine designs which neglect biomechanical considerations. You may have noted that the writer has already indicated that his ideal human engineering program would not only gather the basic data, but also disseminate and make it available to others who can use it. The study of the human being is within the province of biological investigators, who must take on the responsibility of translating this knowledge and working with the engineering profession in its application. A reversal of this experience has occurred in the development of prosthetic devices. Here, it was found that the medical people were in dire need of engineering information. This is only another single instance where professional teamwork was required in order to satisfy the needs. In other words, let us recognize the need for group endeavor, with each member of the group contributing his special skill for the benefit of the rest; at the same time, each partner should attempt to understand the contributions of the rest of his group.

In concluding the portion of our presentation of a human engineering program, there remains one additional item. Up to now, we have talked about modifying equipment, machines, vehicles, and even prosthetic devices, in terms of human characteristics. An alternative procedure is to modify the individual. This is not a proposal to step up the rate of emergent evolution. Rather, I am thinking of training procedures and devices. If we could really foresee the day of full automatization or push-button operations, then the need for special effort in the field of training might be overlooked. It seems

highly probable, however, that even the best human engineering endeavors will still leave *Homo sapiens* in behavior situations which are complex and difficult. Therefore, in order to round out our full program, the writer believes that personnel training is a part, or at least a necessary adjunct, of our total plan.

Some Recent Findings in Human Engineering. In the final section of this paper, we shall illustrate, by reference to the results of specific research investigations, the sort of information that will be forthcoming as the program already outlined becomes effective. No attempt will be made to present a complete review of each area because of the limitations of space, and because other authors will cover some of the topics more adequately.

The first area which we mentioned was the fitting of the individual into atypical environments. A most striking example of this type of problem has been brought about by the development of high-speed piloted aircraft. It is difficult to imagine the visual, acoustic, and vibrational environment for the pilot who flies straight and level at over 600 miles per hour. In so far as he uses visual contact reference, his whole visual field moves at much greater rates, so that he approaches the limits of ordinary reaction time in sensing and responding to stimuli. What was a mild bump at 160 miles per hour now becomes a violent jar, so that the pilot must wear crash gear to keep from knocking himself unconscious. If the pilot wants to perform a turn, he is now in danger of blacking out, due to positive angular acceleration.

In order to study the effects of centrifugal acceleration, so as to develop protective measures eventually, several human centrifuges have been developed. Data already obtained in this field of aviation medicine can be reviewed for illustrative purposes.[1] Even when the pilot is experiencing a 2 G force, there is a marked feeling of pressure, as he is forced into his seat and his extremities become difficult to lift. Response time is increased accordingly. At 3–4 G, these sensations of heaviness are exaggerated and great effort is required in order to move the hands and feet; erect posture is difficult to maintain. Between 5 and 8 G, unconsciousness or coma develops. This state is preceded by a blacking-out of the field of vision, probably due to the loss of blood from the head and face. The pilot's value, as a controller of his machine, is practically nil at this point. Yet the accelerative forces about which we have been speaking are well within the stress limits of the aircraft structures. Whether it will be possible to bring the man up to the tolerance limits of his aircraft is difficult to say. It may be that here we have a true instance of engineering possibility not being realized because of human weakness.[8, 10]

Let us turn now to some illustrative research in the field of instrument displays. A large percentage of visual indicators are of the clock-face type. A question which faces the designer of this kind of instrument is the number of graduation marks to put around the scale. One might guess that it would be extremely easy to ascertain the answer to this question. As a matter of fact, it has taken a number of years and several comprehensive experiments to begin shedding final light on this problem.

One of the first experiments was done during World War II by Loucks,[7]

who used aircraft tachometer dials with various numbers of markings. It was found, on the basis of short exposures, that the percentage of errors was greatest for the dial with the largest number of graduations. He concluded, therefore, that the cleanest dial, from the standpoint of design, gave the most accurate readings. Grether and Williams[5] measured speed and accuracy of reading dials ranging from 1 to 4 inches in diameter, and from 5 degrees to 40 degrees in angular separation of graduations. They found an increase in accuracy of dial reading as the dial diameter increased, except for the case with 40 degrees angular separation of graduation marks; in the latter case, there was a decrease in accuracy when dial diameter exceeded 2 inches. They then plotted all their data on a single curve relating accuracy to length (not degrees) of graduation interval. Regardless of dial diameter and angular separation between graduation marks, the error was found to decrease as the linear distance between intervals increased up to $\frac{1}{4}$ inch, with little gain thereafter. The most recent experiment on this matter is that of Kappauf,[6] who found, contrary to Loucks, but with a different method of measurement, that accuracy increased with an increase in the number of graduation marks. A 5-unit dial was better (in terms of error and speed of reading) than a 10-unit dial. On the other hand, a 1-unit dial was only slightly better than the 5-unit dial.

Grether[4] explains these diverse findings by noting that quantitative dial reading errors may be of two kinds, interpretation and interpolation. Interpretation errors would be increased by an increase in the number of graduations because of the greater ambiguity of the specific marking approached by the pointer. Interpolation errors, on the other hand, are decreased by an increment in number of dial markings because the reader has less difficulty in deciding where the pointer is between scale divisions. It is to be hoped that Dr. Kappauf will discuss this problem further in his paper in this monograph.

The third major area of human engineering concerns the specification of the characteristics of machine controls. One of the most significant problems here is the basic motor capacity of the average individual. The therblig notation system of the motion-and-time study engineer has long been a standard method for classifying the different elements of work performance. In 1947, however, Brown and Jenkins[2] proposed a new classification, which may serve as an impetus for further needed research. It is impossible to do justice here to a complete description of their proposed classification. Fundamentally, however, they separate types of motor reactions into three distinct classes: (1) static reactions, which includes all instances where a body member is required to be held in a fixed position in space; (2) positioning reactions, wherein the members of the body are moved from a position of rest to a specified position in space, the terminal accuracy being of primary significance; and (3) movement reactions, which are movements of the bodily members at given rates, in given directions, along specific paths.

Subsequent to this analysis of motor reactions, Brown[3, 11] has completed several investigations on discrete and positioning responses. Mention of some of these results is warranted because of their novelty and significance.

One of these studies[11] was intended to ascertain the accuracy with which individuals performed positioning reactions in the absence of visual corrective cues. The subjects were required to move the right arm and hand from a point of rest to a terminal position located either .6, 2.5, 10, or 40 cm. distant. After an exposure of 2.5 seconds to one of these four extents, the reactions were made in total darkness. Movements were made in both horizontal and vertical planes in various directions. It was found that there was a tendency to overshoot the intended mark at shorter distances and to fall short at longer distances. One exception, attributed to the effects of gravity, was noted for all distances in the vertical plane when direction of movement was from top toward bottom. The percentage of error decreased and the variability increased with each increment in distance. A plot relating speed of movement to distance was found to be of the form $y = ax^b$.

Because of the possible significance of speed of bodily movements to equipment design and job operations, Brown[3] has just completed a follow-up study to determine the effects of speed-up instructions on positioning reactions. The motions were all in the horizontal plane. Despite the emphasis on speed in the instructions to the subjects, there was no increase in the average reaction time. Although primary-movement time was decreased, the total-movement time was not. There was also a decrease in the time spent in making the fine, secondary adjustments following the initial gross approaches to the terminal point. Brown concludes that attempts to speed one's movements may produce apparent increases in speed which, in terms of overall efficiency, yield little genuine improvement.

Our final area in a program of biomechanics was designated as the study of man-machine systems.[9] Rather than present an illustrative sample of results recently obtained in this field, it seems preferable to outline briefly a method of attack on such problems. This outline has been proposed by the Systems Research Laboratory of the Johns Hopkins University. The paper by Dr. Chapanis represents one phase of the Hopkins attack on the overall efficiency of man-machine combinations. Methodology is one of the main determinants of progress, and this project's contribution to it may be of far-reaching significance.

The end point in our psycho-physical systems analysis is to specify (1) the most efficient number of human operators, (2) the number and characteristics of various equipment components, and (3) the best arrangement and layout of the men and their gear.

To say unequivocally that we can now make such appraisals would be an exaggeration. What has actually been accomplished is the formulation of a systematic approach, a theoretical scheme for attacking problems of this nature.

Space and the tentative nature of our theoretical structure prevent an elaboration of more than a skeleton outline of the method of procedure. The first step is to analyze and itemize all the connections between all the components of the system. Thus, we list all connections between men and machines, men and men, and machines and machines. These connections, which are termed links, will be found in a majority of cases to be visual,

auditory, or control links. Having determined what these links are, it now becomes necessary to estimate the importance of each one. There are two criteria for determining importance of link value. One is the frequency with which each link is used, and the other is the importance of that link when it is used. In the case of a system which already exists, the link-value with respect to frequency can be determined merely by tabulating the number of times that a particular link occurs. For determining the link importance value, we have to turn to a more qualitative measure, which involves psychological rating scale techniques. Having estimated link use value and link importance value, we combine these two measures into a single score, which is used in the final rearrangement of the whole system. This last step consists in arranging the overall link values in order of size. By using a graphical plot, and juggling the link values around in this manner, we find a proposed solution to the particular systems problem.

This approach to systems design is admittedly qualitative and not rigorously scientific. Whether we thus possess the essence of a basic and valid theoretical construct is not yet clear. On the other hand, this approach has been used in a number of military circumstances and has been found to increase the overall efficiency of complicated men-machine linkages. Further research and application by motion-and-time engineers and psychologists is needed.

This concludes the section on recent findings in the general field of human engineering. An illustration of research on the aspect of "modifying the man" is being omitted for two reasons: (1) the reader may object to the inclusion of research concerning training methods and devices in the field of human engineering; and (2) most of the efforts in this field are specific and piecemeal in character, at least in so far as manipulative learning is concerned.

Summary and Conclusions

The writer has attempted to give a résumé of the manner in which this so-called field of "human engineering" arose and to specify what is encompassed by the term. Also presented was an outline of major topics, which included human engineering efforts within the experience of the writer. It is suspected that the illustrative experiments cited as representative of these major topics are either very familiar or completely foreign to most readers. If this is so, it represents one of our difficulties. Human engineering is not a science or field of endeavor by itself. Rather, it is a technical service which our society now demands. Recent interest in the phrase merely indicates that individuals from many professions, particularly the engineering and biological sciences, have discovered that they can and should be of mutual assistance in solving the problems of fitting man to the complexities of his contemporary work situation. Meetings of this sort can serve the highly useful function of helping the diverse individuals who are called upon to accomplish this task to understand and cooperate with each other.

Bibliography

1. Armstrong, H. G. 1946. Principles and Practice of Aviation Medicine. Houghton Mifflin, New York.

2. Brown, J. S. & W. O. Jenkins. 1947. An analysis of human motor abilities related to the design of equipment and a suggested program of research. In: P. M. Fitts (Ed.). Psychological Research on Equipment Design. AAF Aviation Psychology Program Research Report **19,** U. S. Govt. Printing Office.
3. Brown, J. S. & A. T. Slater-Hammel. 1948. The effect of speed-up instructions upon the performance of discrete movements in the horizontal plane. ONR Report **57-2-3**.
4. Grether, W. F. 1948. The design of instrument dials for ease of reading. Paper presented before SAE National Aeronautic and Air Transport Meeting, April, 1948.
5. Grether, W. F. & A. C. Williams, Jr. 1947. Speed and accuracy of dial reading as a function of dial diameter and angular separation of scale divisions. In: P. M Fitts (Ed.). Psychological Research on Equipment Design. AAF Aviation Psychology Program Research Report **19,** U. S. Govt. Printing Office.
6. Kappauf, W. E. 1947. Design of instrument dials for maximum legibility: I. Development of methodology and some preliminary results. USAF, AMC, Aero-Medical Laboratory Memorandum Report **TSEAA-694-1L**.
7. Loucks, R. B. 1944. Legibility of aircraft instrument dials: a further investigation of the relative legibility of tachometer dials. AAF School of Aviation Medicine, Randolph Field, Texas. Project **265,** October, 1944.
8. McFarland, R. A. 1946. Human Factors in Air Transport Design. McGraw-Hill. New York.
9. Mead, L. C. 1947. Human factors in engineering design. Soc. Auto. Eng. J. **55** (12): 40–46.
10. Mead, L. C. 1948. Application of human engineering to flight problems. J. Aviat. Med. **19:** 45–51.
11. Slater-Hammel, A. T. & J. S. Brown. 1947. Discrete movements in the horizontal plane as a function of their length and direction. ONR Report **57-2-2.**

HANDBOOKS OF HUMAN ENGINEERING DATA

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Reasons for the Existence of Handbooks

During the last one hundred years, the science of experimental psychology has been accumulating quantitative information on the behavior and experience of human individuals. Fernberger[3, 4] has plotted the steady rise of publications in psychology by different language groups during the period from 1894 to 1945. If we cite the data for publications in the English language alone, we find somewhat less than 2,000 titles in the period from 1894–96 and more than 11,000 titles in the period from 1933–35. The average yearly publication rate from 1926–45 was 3,013. It is evident that a large body of factual information has been obtained by psychologists.

From time to time, psychologists have attempted to sort this information into convenient form for purposes of review and analysis. The "Psychological Bulletin" has for many years served as an outlet for the review of literature in particular fields. Murchison's[7] "Foundations of Experimental Psychology" and his "Handbook of General Experimental Psychology"[8] have performed a necessary function for the student of psychology in bringing together periodically the growing literature. A new edition of this handbook is now being prepared under the editorship of S. S. Stevens of Harvard.

These books, however, have not been handbooks in the sense of handbooks in physical science or engineering. They have been, rather, critical reviews of literature. The handbook in engineering, chemistry, *etc.* is usually a volume containing the quantitative data on which the science is based and is also a book in which the persons who wish to apply the science may find the essential information for such application. With the exception of R. S. Woodworth's[9] work on the preparation of "Psychological Data Pertaining to Errors of Observation" for the "International Critical Tables," published in 1926, psychologists have not prepared a comprehensive quantitative guide to the important facts of human behavior. The Systems Engineering Laboratory at Johns Hopkins has published an excellent series of lectures on human engineering[2] and is now engaged in writing a text book for courses in human engineering.

W. S. Hunter[5] has observed that the demands of World War I were responsible for the phenomenal growth of the mental testing and personnel classification side of applied psychology, and, that during World War II, work on increased efficiency in the man-machine relationship was the most important outcome for psychology. Certainly, the present expansion of what has been called, respectively, applied experimental psychology, biomechanics, engineering psychology, and human engineering, has been a function of military necessity. We were handicapped during World War II by the lack of a handbook of human engineering data. We were further handicapped by the fact that much of the important data necessary for an

effective function in human engineering has not yet been obtained. As technical aide to the Applied Psychology Panel of OSRD during World War II, the author became aware of this need and resolved to try to produce such a handbook, realizing that many gaps would exist in important information. At least, we now know more about the gaps and what it will take to round out a complete picture of human behavior. How to go about filling the gaps will be the subject of my concluding remarks.

E. G. Boring, in his historical preface to Bartley's[1] "Vision—A Study of Its Basis" says, "Because the purpose of science is economy of thinking, and when, in spite of its generalizations, science gets too cumbersome for easy comprehension, there have to be handbooks. . . . If the facts of any subject cannot be subsumed under a few big theories, at least they can be brought together, systematized, related, and made accessible. Handbooks do just that and they are necessary tools of science."

If the preparation of our handbook requires more justification, we may quote the words of William James, who, in 1907, said,[6] "We ought somehow to get a topographic survey made of the limits of human power in every conceivable direction, something like an ophthalmologist's chart of the limits of the human field of vision; and we ought then to construct a methodological inventory of the paths of access, or keys, differing with the diverse types of individual, to the different types of power. . . . So here is a program of concrete individual psychology, at which anyone in some measure may work. It is replete with interesting facts, and points to practical issues superior in importance to anything we know."

Scope of the Handbooks

Exhibit A, in the appendix to this paper, is a recent revision of the table of contents of the handbooks now being prepared by the staff of Contract N6ori-199 at the Institute for Applied Experimental Psychology at Tufts College. I speak of handbooks, rather than handbook, because we are preparing two handbooks, one for an audience of engineers, naval officers, and others who have a technical background but no specific training in psychology, and the second for the professional psychologist, or the human engineer. The table of contents will be nearly identical for both books, but the edition for engineers is being written with a minimum of the technical jargon of psychology. Exhibit B, the reaction time section of the "Engineer's Handbook," to which I shall return in a moment, was written from a larger section of the "Psychologist's Handbook," by Mr. John C. Armington, a graduate electrical engineer, who is now a graduate student in the Department of Psychology at Tufts. In general, we prepare the "Psychologist's Handbook" sections first, and then the corresponding "Engineer's Handbook" section.

To return to the table of contents in Exhibit A, it will be noted that our concept of human engineering is rather broad. It includes data from anthropometrics, sensory psychology and physiology, experimental psychology, social psychology, industrial psychology, environmental physiology, and pharmacology. Human engineering has the same relation to

the sciences of biology, psychology, physiology, anthropology, anatomy, and the social sciences as machine engineering has to physics, chemistry, and geology.

Exhibit B, a preliminary draft of the reaction time section of the "Engineer's Handbook," will illustrate the kind of information to be expected in this book. We operate on the principle that a good table or graph is worth a thousand words. We want to provide the maximum amount of quantitative information consistent with a basic understanding of the processes involved. The approach is to (1) define terms; (2) present established generalizations and their supporting data on (a) stimulus conditions, (b) characteristics of individuals affecting the function; and (3) present a brief summary of rules to follow to predict and control the function.

Some of the readers may be interested in the organization of the staff of the handbooks project. Dr. Dorothea J. Crook has been the project director, with Dr. Arthur C. Hoffman, Dr. Emily Willerman, Dr. Ruth Bussey, and Mrs. Margaret Raben as senior staff members. Several secretarial assistants and a part-time photographic technician complete the group working at Tufts College. Dr. Bussey has collected much information from the service libraries in Washington in war-time reports of human engineering work. I have been serving as editor.

In the organizational period of the contract, we had the benefit of the advice of a board of editorial consultants, including Dr. J. G. Beebe-Center, Harvard, Dr. Leonard Carmichael, Tufts, Dr. Paul M. Fitts, Aero Medical Laboratory, Dr. W. S. Hunter, Brown, Dr. Henry A. Imus, Office of Naval Research, Dr. W. E. Kappauf, Princeton, Dr. D. G. Marquis, University of Michigan, Dr. Dael L. Wolfle, American Psychological Association, and Dr. R. S. Woodworth, Columbia. Dr. Leonard C. Mead, Special Devices Center, Office of Naval Research, is the Scientific Officer for the contract.

One principle of operation may be worth further mention. After considerable discussion, it was decided that the reading, abstracting, and assembly of first drafts of sections should be carried out by the central organization at Tufts. When a section has been finished in first draft, we request critical comment from experts in the various fields. The next draft of the section incorporates these critical comments. This technique for insuring comprehensive coverage and substantially correct conclusions has worked, we think, rather well.

We should return to the shortcomings of human engineering data. The sampling problem is first. Nothing is more certain in human engineering data than individual variation. The samples of human performance which we now possess are recognized as inadequate from many points of view. Our society has, so far, supplied adequate population samples in the fields of public opinion, intelligence, and the sexual behavior of the human male. Many human functions reported in the handbooks will be based upon samples taken from college sophomores, and, when we get a population of over 100 cases, we are reasonably happy. Much of military psychological research during World Wars I and II was based upon samples of adequate size, but pre-selective factors were present to restrict the generality of the

data. In order to determine the limits of human performance with precision, it will be necessary, in the future, to sample the behavior of large and unselected groups of individuals.

The second major difficulty with human engineering data is more of an annoyance than a gap. We need standard methodology, standard phraseology, and standard test equipment. The human engineering problem is a multi-variable problem, with simultaneous interaction of variables. One way to bring order into the chaos of slightly different experimental procedures is to do as the physical sciences have done, namely, establish operationally defined standards for units, variables, subjects, and procedures. I can report that some progress has been made in this direction for the field of applied visual research by a subcommittee of the Army-Navy-NRC Vision Committee. But we need standardization of procedures in all human engineering fields.

There are many real gaps in our present knowledge. The fields of attention, applied perception, motor skills, and thinking cry out for systematic population sampling by techniques already well established.

These difficulties have caused me to ponder the most efficient way for obtaining data for the second editions of these handbooks. It seems to me that we need a Bureau of Human Engineering Standards, which would operate in much the same way as does the Bureau of Standards for the physical sciences. With such an organization and ten years of concentrated data collection, employing known methods, the precision of human engineering data could be greatly increased and the gaps filled.

Bibliography

1. Bartley, S. H. 1941. Vision: A Study of Its Basis. Van Nostrand, New York.
2. Chapanis, A., W. R. Garner, C. T. Morgan, & F. H. Sanford. 1947. Lectures on Men and Machines. An Introduction to Human Engineering. Systems Research Laboratory, Baltimore. Restricted.
3. Fernberger, S. W. 1938. Publications, politics and economics. Psychol. Bull. **35:** 84–90.
4. Fernberger, S. W. 1946. On the number of articles of psychological interest published in the different languages: 1936–45. Am. J. Psychol. **59:** 284–290.
5. Hunter, W. S. 1946. Psychology in the war. Am. Psychologist **1:** 479–492.
6. James, W., from Bender, I. E., H. A. Imus, J. W. M. Rothney, C. Kemple, & M. R. England. 1942. Motivation and Visual Factors. Dartmouth College Publications, Hanover, N. H.
7. Murchison, C. (Ed.) 1929. The Foundations of Experimental Psychology. Clark University Press, Worcester, Mass.
8. Murchison, C. (Ed.) 1934. A Handbook of General Experimental Psychology. Clark University Press, Worcester, Mass.
9. Woodworth, R. S. 1926. Psychological data pertaining to errors of observation. International Critical Tables **1:** 92–95.

Appendix

EXHIBIT A: HANDBOOK OF HUMAN ENGINEERING DATA

(For Design Engineers)

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Prepared by: Staff, Handbook of Human Engineering Data; Tufts College Institute for Applied Experimental Psychology.

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EXHIBIT B: *Excerpt from* HANDBOOK OF HUMAN ENGINEERING DATA (For Design Engineers)

Reaction Time Section

Prepared by: Staff, Handbook of Human Engineering Data; Tufts College Institute of Applied Experimental Psychology.

The time taken by a person to respond after he has been given the proper signal is known as his reaction time (RT). For example, the time taken by a truck driver to place his foot on the brake pedal after he sees a red traffic light is his reaction time. The time taken by a quartermaster to read his watch, after having been given the signal, "mark," by the navigator, is also an RT.

In laboratory measurements of RT, a precise electric stop clock, or chronoscope, is used. The clock is often wired to two telegraph keys, A and B. Pressing key A starts the clock; pressing key B stops it. Pressing key A also turns on some type of signal or stimulus such as an electric light or bell. The person who is making the measurement of RT pushes key A, starting the clock and turning on the signal. As soon as the subject or person whose reaction time is being measured perceives the signal, he presses key B, thereby

stopping the clock. A warning signal is sometimes given a short time before the actual stimulus. The subject then knows when a stimulus is to be expected. The time taken by the subject to respond in this manner is his RT and may be read from the clock's dial. Measures of reaction time are usually expressed in milliseconds (ms). An RT measured in this manner is called a simple RT. In other situations, however, a person must decide what response must be made to a particular signal. For example, if a truck driver is approaching an intersection, and another car is also approaching the intersection from a different direction, the driver must decide whether to step on the brake and let the other car pass, or to step on the accelerator and beat the other to the crossing. The time taken for the driver to respond in this case is called a complex RT.

In a simple RT situation, an individual is merely required to make a response to a given signal. In a complex RT situation, several different signals and responses must be distinguished. All statements made below are based upon simple reaction time only, except when complex reaction times are specifically mentioned. All measures of time in this article are expressed in milliseconds, unless labeled otherwise. The signal to which a response is made is called a stimulus.

RT is important, inasmuch as it provides a measure of the minimum amount of time required to make a response under optimum conditions. Even under emergency conditions, a person is able to respond no more quickly than his minimum RT for that situation. RT also provides some measure of alertness. An individual's RT becomes longer as he pays less attention to his task.

TABLE 1

EFFECT OF TYPE OF STIMULUS UPON REACTION TIME

Stimulus	RT *in ms.*
Vestibular[1]	600 ± 110
Tactual[9]	210 ± 040
Visual[2,3,4]	200 ± 080
Electric shock[5]	155 ± 020
Auditory[6,7,8]	150 ± 050

General Information Concerning Reaction Time

The material included in this article has been divided into three sections: Part I lists the effects of the stimulus upon RT; Part II explains how RT is affected by the person making the response; and Part III pertains to complex RT situations. RTs quoted below are the average values obtained from the studies upon which the tables are based. The values following the plus or minus signs indicate the RT range in milliseconds of approximately 95 per cent of the persons measured. For example, if an RT is quoted as 150 ± 50 ms., the average RT of all the persons measured was 150 ms., and 95 per cent of the individuals had RTs which were between 100 and 200 ms.

I. *Concerning the Characteristics of the Stimulus. General.* Stimuli or signals are classified according to the sense or receptor which is used. Visual stimuli involve the use of the eyes; auditory, the use of the ears, *etc.* Tactual receptors include the senses of warm, cold, touch, and pain. Vestibular receptors, found chiefly in the inner ear, enable us to judge the position of our body relative to forces of gravity and acceleration. They make it possible for a person to tell whether he is falling or being rotated. For example, the sinking feeling that is detected by a passenger in a rapidly descending elevator is a result of stimulation of vestibular receptors.

RT varies with the type of stimulus or signal given. The usual length of RT as a function of the stimulus is given by the values in TABLE 1. The values given were obtained under optimum conditions. In practice, the relative lengths of the RT may be expected to vary in the same order with respect to type of stimuli, although the actual times may be somewhat different.

Strength of Stimulus. As a general rule, if the strength of a stimulus is increased, reaction time is shortened.[10,11] Increase in the intensity of the signal will be most effective for those stimuli which are initially weak. There is an optimum value which is determined by the particular circumstance in which RT is measured. Stimuli which are too intense startle the person making the response, thereby causing him to have a longer RT.

Simultaneous Stimuli. RT is shorter when several stimuli are presented together

than when a single stimulus is used (TABLE 2). For instance, a man will react more quickly to both a red light and an alarm bell than he would to either of them presented alone. It may be noted that the values given in this table do not agree in all cases with those given in TABLE 1. This gives some indication as to what extent psychological measurements may vary. The differences may be due to a factor such as intensity of the stimulus, *etc.*, which was unspecified in the experimentation upon which the tables were based. In general, addition of a second stimulus may be expected to decrease by 7 per cent the RT in a situation in which only one stimulus is used.

Distraction. In general, distractions lengthen RT. By distraction is meant some type of disturbance such as flashing lights or noises. Intermittent distractions prolong RT

TABLE 2

EFFECTS OF SEVERAL STIMULI ON REACTION TIME[16]

Stimuli	RT *in ms.*
Visual	175 ± 25
Electric shock	170 ± 30
Auditory	150 ± 25
Electric shock and auditory	150 ± 30
Electric shock and visual	150 ± 30
Auditory and visual	145 ± 20
Auditory, electric shock, and visual	135 ± 20

TABLE 3

EFFECT OF CHANGE IN INTENSITY UPON REACTION TIME[48]

$\frac{\Delta I}{I}$ Ratio of Change in Intensity to 100 per cent RT is the Minimum Possible RT. Table Is Based upon Visual Stimuli.

RT%	$\frac{\Delta I}{I}$
100	4
104	1.85
108	1.24
116	.75
124	.51
136	.27
146	.19
164	.14
200	0

These results were obtained under the most favorable conditions and are the fastest voluntary responses possible. RT in a practical situation would be much longer, and should be determined by experimentation if possible.

to a greater extent than do continuous distractions.[17] For example, persons working near an airport are more disturbed by noises of planes taking off and landing than is the pilot who is exposed to the sound continuously. Distraction effects are greatest when the distraction and the main stimulus are of the same type. For example, a bell is heard with more difficulty in a noisy room than in a quiet one.

Interference. Reaction time is lengthened if a subject is performing some other task while responding to stimuli. For example, in one experiment persons were required to close a telegraph key in response to signals presented at irregular intervals from an electric buzzer. At the same time they were required to observe a series of advertisements which were projected upon a screen.[19] Under this condition, their RT was 25 per cent longer than when they were required only to respond to the buzzer.

Preparation. If the subject is prepared and waiting for the stimulus, RT is shortened. A 2- to 4-second warning signal before the stimulus shortens RT by 30 to 50 per cent. Longer preparation periods shorten RT to a lesser extent.[20]

Effects from Maneuvers. A pilot's reaction time, after having completed airplane maneuvers, is 8 per cent shorter if the maneuvers were conducted in view of the earth (contact flying) than if conducted solely by instruments. If a plane has been tipped, a pilot requires more time to restore it to level flight by using instruments than he does if the ground is visible.[21]

Change in Intensity. The greater a change in intensity of the stimulus, the shorter will be the reaction time to this change.[48] RT is 5 to 10 per cent shorter for a decrease than for an increase in the intensity of a stimulus. RT is slightly shorter for the cessation or stopping of a stimulus than it is for the onset or starting of a stimulus.[49]

Position of Response Key. For short RTs, the response key must be placed in a favorable position. If a person has to stretch out an arm or leg in order to respond, RT will be lengthened. The most favorable position must be found by experiment.

TABLE 4

EFFECT OF AGE AND SEX UPON VISUAL AND AUDITORY REACTION TIMES IN MILLISECONDS[50]

Age years	*Male*		*Female*	
	Visual stimulus	*Auditory stimulus*	*Visual stimulus*	*Auditory stimulus*
1–10	340 ± 200	340 ± 200	620 ± 350	590 ± 380
11–20	240 ± 80	230 ± 82	320 ± 68	310 ± 82
21–30	220 ± 70	190 ± 68	260 ± 40	200 ± 145
31–40	260 ± 92	240 ± 28	340 ± 75	300 ± 225
41–50	270 ± 52	250 ± 95	360 ± 70	300 ± 75
51–60	380 ± 115	370 ± 160	440 ± 145	420 ± 170

TABLE 5

REACTION TIME AS DETERMINED BY THE LOCATION OF STIMULUS

Angle from center of visual field, degrees.		*Reaction time in ms.*
On the side of the nose	45°	205
	30°	192
	10°	187
	3°	190
Dead ahead	0°	185
On the side of the ear	3°	191
	10°	194
	30°	197
	45°	215

II. *Concerning the Characteristics of the Person Making the Response. General.* RT, in a particular situation, depends upon the particular person who is responding. Although one group of individuals may respond favorably in an RT situation, other persons in the same situation may respond more slowly or rapidly than is desired.

Personal Factor. Individuals who react quickly in one RT situation will tend to react quickly in all RT situations.[22]

Speed Factor. There is some evidence that RT is related to personal speed factors; *i.e.*, a "good track man" may have a shorter RT than a poor one. Such relationships, however, cannot be depended upon.[25]

Sex. RT is affected by the sex of the subject. Men tend to have RTs 5 to 10 per cent shorter than those of women in any particular RT situation. Sex differences may disappear as persons become accustomed to the task.[23]

Age. RT varies with the age of the individual. For visual and auditory stimuli, the age of shortest RT is about 25 years.[24]

Body Parts. In general, the speed of response is not affected to a significant degree by the part of the body used to make the response.[26,27,28] An individual may be expected

to respond as quickly with his hand as with his foot. The position of the response key relative to the body, however, is important. If a subject is required to stretch his arm or leg to make a response, RT will be prolonged. The kind of movement made by the responding member is also important; most responses for which figures are quoted in this chapter were made by removing the responding member from a key or pedal as quickly as possible. If a subject were required to turn a knob as a response, RT would be much longer.

Receptor Used. In general, stimulation of either the right or left eye alone will produce the same RT. Stimulation of both eyes together may shorten RT up to 15 per cent.[29]

Location of Stimulus. Under normal lighting conditions, stimuli which are directly fixated are responded to more quickly than those in the periphery of the visual field.[30]

Adaption. When a person enters a dark room after having been in a light place, he cannot see well at first. After he has been in the dark room for some time (10 to 30 minutes), however, he is able to see better. His eyes are then "dark-adapted." If he leaves the dark room and enters the light room again, he will squint his eyes until they adjust themselves to the more intense light. When his eyes are adjusted to the light room, they are "light-adapted." If a person is light-adapted, his RT will be fastest

TABLE 6

REACTION TIME AS A FUNCTION OF THE NUMBER OF DISCRIMINATIONS[44,45]

Number of stimuli to be distinguished (visual stimuli)	*Complex* RT, *ms.*
1	290 ± 60
2	475 ± 120
3	566 ± 200
4	656 ± 300
5	741 ± 425

TABLE 7

EFFECTS OF SEX AND STIMULUS UPON COMPLEX REACTION TIME[46]

Stimulus	*Men's* RT (*ms.*)	*Women's* RT (*ms.*)
Light	520 ± 70	565 ± 100
Horn	510 ± 90	550 ± 110

for stimuli in the center of the visual field. If the individual is dark adapted, RTs will be slightly shorter for stimuli of low intensity which are slightly to one side of center of the visual field.[31,32]

Practice. An individual's RT may be shortened up to 20 per cent by many repetitions of the task. 200 trials or repetitions will be adequate for optimum performance in most cases.[33, 34, 35, 36]

Differences between individuals, however, do not disappear with practice. The person who had a longer RT before practice will still have a relatively long RT after practice. Training to respond more rapidly to one type of stimulus will enable a person to respond more quickly to all types of stimuli.

Fatigue. Strenuous work will prolong an individual's RT, on the average, up to 65 per cent.[40] The time which has passed since rising from bed has little effect upon RT.[40]

Incentive. Knowledge of the results of preceding RT performances and punishment after a poor performance will shorten RT.[38] By punishment is meant a mild electric shock immediately following a poor performance. Punishment is more effective than knowledge of results.[4]

Reflexes. Reflexes are responses which are made to stimuli without any voluntary effort. Reflexes require much less time than RT situations. The jerk of the leg which occurs when the knee cap is tapped with a rubber hammer is an example of a reflex. A wink which occurs when the eyes are exposed to a bright light is also a reflex. No relationship has been found between the time taken for a bodily reflex and an individual's RT.[43]

III. *Concerning Complex Reaction Time. General.* Reacting to complex situations, in general, requires more time than reacting to simple situations. The length of time required to make a particular complex reaction varies with the complexity of the situation.

Number of Stimuli to be Discriminated. The greater the number of stimuli between which an individual must discriminate, the longer will be his RT. If a person is required to watch several dials, his RT to any one dial will be longer than if he has to observe only one dial.

Foot Pedal Braking. In a "dummy trainer" automobile, a complex RT situation was arranged so that the subject was required to push a brake pedal in response to either a red light or to an automobile horn. RT was about 550 ms.[46] In a practical situation, RT is dependent upon the attention and alertness of the driver. Also, the driver must pay attention to many more stimuli than are included in a laboratory situation. Under actual driving conditions, RT will be at least two to three times longer.

Practice. Complex RT can be shortened with practice. In pushing a brake pedal in response to a red light, RT can be shortened 20 per cent.[47]

Cognitive Reaction Time. If a subject is required to recognize a stimulus before responding, it is known as a cognitive or perceptual RT situation. In a cognitive RT situation, the subject does not respond immediately after perceiving the stimulus, but responds only after he recognizes or realizes what the stimulus is. For example, if an individual is being stimulated with numbers, he does not press the response key as soon as the number is presented, but waits until he knows what the number is and then presses the response key.

Stimulus Effect. Cognitive or recognition RT is dependent upon the complexity of the stimulus; recognition RT may take up to 1 second.

Table of Rules For Shortening Reaction Time

(1) Place the response key (brake pedal, throttle, etc.) in that position relative to the body which produces the most rapid responses.
(2) Use that type of stimulus which gives a short RT (*i.e.*, auditory, or electric shock).
(3) Use several simultaneous stimuli if possible (*e.g.*, flashing red light and alarm bell).
(4) Place the stimulus where it is most apt to attract attention (*e.g.*, place a signal light directly in front of the eyes).
(5) Use a stimulus of optimum intensity. Generally, a loud bell is better than a weak one. A bell that is too loud, however, startles the individual and prolongs his RT.
(6) Eliminate all distracting influences. A shorter RT can be obtained in quiet surroundings.
(7) Give the person advance warning of the stimulus if possible.
(8) Select persons who have naturally shorter RTs (young adult males).
(9) Instruct the individual and give him ample practice.
(10) Avoid heavy work immediately preceding a RT situation.
(11) Avoid complex RT situations if possible. The fewer the number of stimuli between which a person must discriminate and the fewer the number of responses he is able to make, the shorter will be his RT.

Bibliography

1. Baxter & Travis. 1938. J. Exp. Psychol. **22:** 277–282.
2. Baxter. 1942. J. Exp. Psychol. **31:** 430–437.
3. Forbes. 1945. J. Exp. Psychol. **35:** 153–162.
4. Todd. 1912. Arch. Psychol. (25): Table 1.
5. Woodrow. 1916. J. Exp. Psychol. **1:** 285–318.
6. Todd. See ref. 4.
7. Baxter. See ref. 2.
8. Hovland & Bradshaw. 1935. Psychol. Forsch. **21:** 50–55.
9. Lanier. 1934. J. Exp. Psychol. **17:** 371–399.
10. Froeberg. 1907. Arch. Psychol. (8): Tables 7, 8, 23, & Fig. 2.
11. Woodrow. 1915. Psychol. Rev. **22:** Table IV.
12. Froeberg. See ref. 10.
13. Wells. 1913. Psychol. Monog. **15** (Whole No. 66): Table XXI.
14. Froeberg. See ref. 10.
15. Woodrow. See ref. 11.
16. Todd. 1912. Arch. Psychol. (25): Tables 7 & 3.
17. Evans. 1916. Arch. Psychol. (37): Tables 23, 43, and p. 53.

18. De Silva & Golub. 1937. J. Gen. Psychol. **16:** 279–282.
19. Guilford & Ewart. 1940. Am. J. Psychol. **53:** 554–563.
20. Woodrow. 1916. J. Exp. Psychol. **1:** 23–39; 285–318.
21. Aero Medical Lab. 1947. TSEAA 694–13A.
22. Elliott & Louttit. 1938. Proc. Ind. Acad. Sci. **47:** 223.
23. Reymert. 1923. Scand. Sci. Rev. **2:** 177–222.
24. Koga & Morant. 1923. Biometrika. **15:** 346–372.
25. Westerlund & Tuttle. 1931. Res. Quart. Am. Phys. Educ. Assoc. **2** (3): 95–100.
26. Seashore & Seashore. 1941. J. Exp. Psychol. **29:** 342–345.
27. Reymert. 1923. Scand. Sci. Rev. **2:** 177–222.
28. Baxter. See ref. 2.
29. Miles. 1936. Psychol. Monog. **47:** 268–293.
30. Poffenberger. 1912. Arch. Psychol.
31. Hovland. 1936. J. Gen. Psychol. **14:** 346–359.
32. Lemmon & Geisinger. 1936. Am. J. Psychol. **48:** 140–142.
33. Hovland & Bradshaw. See ref. 8.
34. Miles. 1936. Psychol. Monog. **47:** 268–293.
35. Baxter & Travis. See ref. 1.
36. Evans. See ref. 17.
37. Henmon & Wells. 1914. Psychol. Rev. **21:** 153–156.
38. Rexroad. 1926. J. Exp. Psychol. **9:** 1–18.
39. Evans. See ref. 17.
40. Banerji. 1935. Indian J. Psychol. **10:** 69–79.
41. Forbes. See ref. 3.
42. Johanson. 1922. Arch. Psychol. **54.**
43. Lanier. 1934. J. Exp. Psychol. **17:** 371–399, Table 9.
44. Baxter. See ref. 2.
45. Lemmon. 1927. Arch. Psychol. **15** (94).
46. Elliott & Louttit. 1938. Ind. Acad. Sci. **47:** 220–225.
47. De Silva. 1936. Hum. Factor. **10:** 1–13.
48. Steinman. 1944. Arch. Psychol. **41:** (292): 14.
49. Jenkins. 1926–27. Arch. Psychol. **14** (86).
50. Bellis. 1933. Proc. Soc. Exp. Biol. & Med. **30:** 801–803.

Suggested Readings

Boring, Langfeld, & Weld. Introduction to Psychology: 277–281.
Ruch. Psychology and Life: 276–281.
Woodworth. Experimental Psychology: 298–339.

PROBLEMS RELATING TO AIRCREWS IN AIR TRANSPORT DESIGN

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The future success of civil air transportation will depend primarily on two factors, namely, safety and regularity. In regard to safety, there has been a sharp decline in passenger fatality rates over the past 20 years, and the improvement has taken place while the amount of traffic has been increasing at an extremely rapid rate. Further increases seem likely, but the industry is greatly concerned over the effect that a major accident has on the traveling public. Fear and unreliability of operations play a major role in discouraging newcomers as well as experienced travelers. Although the regularity of services has also been improving, much remains to be accomplished before a perfect safety record can be attained along with 100 per cent regularity. Many capable experts disagree as to the methods of improving safety. Some believe that the answer is to eliminate the human factor by means of flight control systems which are completely automatic. Others believe that the modern transport should be so mechanically simplified and perfected that it can be manually controlled with ease. Regardless of the method which eventually succeeds, there remains an immediate necessity for studying the human problems relating to the aircrews if marked improvements are to be expected within the next few years.

Naturally, the pressure to obtain greater safety and regularity creates certain problems for the aircrews. It is the purpose of this paper to select a number of illustrations of current interest and importance which relate aircrew duties to design features. Since most errors are attributed to human factors, or so-called "pilot error," it seems only logical to analyze what is expected of airmen in relation to the equipment which they must fly. The greatest chances for improvement of safety, efficiency, and regularity depend on improvements in the design and operation of equipment in terms of human limitations and capabilities. Many illustrations can be given of the way in which modern technology has produced machines without adequate concern for the capacities of the operators, and modern air transports offer no exceptions. If aviation is to make significant progress in the immediate future, I feel very strongly indeed that mechanical design must be more intimately related to the physiological and psychological characteristics of the operators. Aircraft must be built around the aircrews rather than fitting them in without due regard for their human characteristics, an occurrence which has happened so frequently in the past

Before showing the importance of this fact in aviation, two illustrations will be drawn from the modern range finder and military tanks. With regard to range finders, our studies showed that the instruments were very accurate and that the human eye was capable of great precision in making visual judgments.[1] When the subjects were looking into the range finders, however, the errors were very great. The range finders had to be re-

designed so that they would fit the physical and psychological characteristics of the operator while sighting on a target. With regard to military tanks, I observed part of the battle at El Alamein in the African desert in 1942 and saw many defects in the tanks from the standpoint of human factors. The ventilation was so poor under desert conditions and the vision outside the tank so limited that many operators opened the turrets to look out and to get fresh air. As a result, many casualties were inflicted on the operators because of lack of protection to the head. As you know, subsequent research based on a consideration of the needs of the operators corrected many of these defects.

Advance Analysis and Design Problems in Air Transport

My interest in the design features of air transports and their implications for aircrews arose from making studies during the initial flights of several new models. Many costly modifications were necessary after the planes were put into service. On one plane, for example, my notebook was filled with more than 85 illustrations of defects or modifications which were necessary or desirable. This suggests that each plane should be more thoroughly flight tested with a full complement of passengers and on various routes before being used in routine passenger service. The cost should be equally distributed among the manufacturers, operators, and the research and development agencies of the government. It has been demonstrated many times that faults in design, such as the changes made in the Constellation and DC-6 after they were put into service, are eventually very costly to all concerned.

Several defects in design that have had a direct bearing on the working efficiency of aircrews are given below. One air transport had windshields with multiple curvatures so that they would be faired to the contour of the plane for aerodynamic efficiency and cleanliness. The distortion of pilot vision and high accident record made it necessary to substitute flat panels and thereby make a change in the production line during the war. The plane was only approximately eight mph slower, but the change in design cost millions in time and money. A study of the human visual factors would have shown the error in such a design in a simple mock-up.

A second illustration is the design of the navigator's table on a flying boat. It not only vibrated excessively; it was built sideways to the forward movement of the plane. The light distribution was poor in that there were 100 foot candles at the back of the table but only 1 or 2 foot candles on the working area. These defects resulted in excessive airsickness and discomfort among the navigators.

A third illustration may be drawn from the confusion arising when controls for operating the flaps and landing gear are too close together or reversed from one plane to another. Inattentive manipulation or mistaken identity resulted in 547 aircraft accidents in one of the services during a 22-month period, January 1943 to November 1944, of which 273 occurred in advanced trainers and 184 in fighters, bombers, and transports. This occurred in the airlines, and such an accident involved one of the outstanding test pilots of the country in the NACA.

In aviation, as in other fields, it often takes loss of life to bring about changes. For example, safety belts were not put over astrodomes until a navigator was blown out into the sea when an explosive decompression occurred. Also, pilots were not properly indoctrinated in the use of oxygen masks for protection against carbon dioxide until several accidents occurred.

How can improvements be brought about? In my opinion, all possible faults in the working area and of the machine as well as those due to the capacities of the operator should be subjected to an advance analysis for preventing accidents. If defects are present, it is only a matter of "time" before some operator "fails" and has an accident. Advance analysis assumes the following considerations.[2] The first involves an operational job analysis which should include a survey of the nature of the task, the work surroundings, the location of controls and instruments, and the way the

Table 1
Specific Pilot Acts Contributing to "Pilot Error"*

Type of error	*Frequency of acts in*	
	Military flying	*Airline flying*
Confusion of two controls	229	31
Forgetting to operate a control	83	41
Improper adjustment of control	83	14
Reversed movement of control	27	—
Inadvertent activation of control	24	6
Unable to reach control	14	—
Total	460	92

* From Fitts and Gordon.[3,4]

operator performs his duties. The second implies a functional concept of accidents, *i.e.*, it anticipates the errors which may occur while the operator is working at the machine. The repetition or recurrence of near or real accidents clearly indicates a need for redesigning. A third consideration relates to human limitations. It should be assumed that no pilot is a perfect one. In fact, he may be far below the ability as judged by the designer. If his duties are too complex, the cumulative burden is great, and he reaches or exceeds his limits of attention and ability. Finally, a wide margin of safety should be provided to eliminate any possible situation which places the pilot near his maximum ability in regard to aptitude or effort, especially when adverse factors enter the picture.

Proof of the fact that errors may arise from defects in design may be obtained from studies of the critical components of airline piloting. Two recent studies have shown how these errors may occur. In one investigation at Wright Field, it was shown that 229 of 460 specific acts contributing to pilot error were due to confusion of two controls, and 83 to forgetting to operate a control.[3] In a second study of airline pilots, 31 of 92 involved the confusion of two controls and 41 forgetting to operate a control (see

TABLE 1).[4] In other words, 68 and 78 per cent, respectively, of pilot error incidence were due to these two causes. These factors become critical toward the end of long flights under adverse landing conditions. As long as defects in design are present, greater care must be given to the selection and training of pilots.

The Flight Engineer's Station. In air transport design, as in other fields, many of the problems have not been satisfactorily solved because of failure to make fundamental analyses relating the job demands to human capacities and abilities. An excellent sample of current interest is the controversy centering around a separate flight engineer's station on the larger transports. The CAB has ruled that "an airman holding a flight engineer's certificate shall be required solely as a flight engineer on all aircraft certificated for more than 80,000-lb. maximum take-off weight, and on all other aircraft certificated for more than 30,000-lb. maximum take-off weight where the Administrator finds that the design of the aircraft used or the type of operation is such as to require engineer personnel."[5] The ruling further states that "the flight engineer will contribute substantially to the reduction of pilot fatigue and resultant accident provoking sequences."[5]

The advantages and disadvantages of including a flight engineer's station in the cockpits of large transports has been discussed in a previous study.[2] The only questions that are being raised here relate to (1) why the decision was made to use a flight engineer after several large transports had been built and certificated for service in domestic operations using a two-man crew and (2) why an 80,000-lb. maximum take-off weight was taken as a criterion for the necessity of having a flight engineer. Furthermore, such a decision might handicap the designers in simplifying cockpits, especially when turbine or jet engines may be introduced in the near future. An advance analysis of the requirements of the aircrew duties against time, especially during take-offs and landings, might have revealed an answer to this problem before rather than after the planes were put into service. Because of the large number of changes which are made during the development of each model, such studies should be made in the manufacturing setting. For example, in the B-377, many changes were made after the cockpit was originally designed. A continuing job analysis of the effect of each change on the performance of the aircrews would provide relevant data on both technical and operating problems.

Various attempts have been made to study the desirability of having a flight engineer's station by an analysis of near accidents. This method is of value because faults in design or operating procedures can be altered in order to prevent their recurrence. An analysis of past accidents is of less value, however, because of the difficulty of reconstructing what actually happened and of determining the precise errors which the pilots or flight engineer may have made. If post-accident analyses are made, it is equally important to determine the number of cases in which flight engineers may have prevented serious mishaps.

An experimental approach to the advance analysis of aircrew duties and accidents would be to use a mock-up of a large multi-engine aircraft which duplicates the instrumentation and controls in simulated flight. For

example, the Dehmel Flight Trainer, which reproduces the cockpit of the B-377 and is being used by PAA, could be adapted to such studies very effectively. The basic components of such equipment comprise electronic computing and analyzing units. Control data are supplied to the mechanism, the response of the aircraft is computed, and the proper signals are transmitted to the control inputs. These are then reproduced as control forces, instrument responses, noise and vibration, and possibly acceleration of the cockpit. Recorders can be attached to all instruments and controls for the simultaneous recording of aircraft behavior.

The types of recording which are available and which should meet all needs are oscillograms, card punching, automatic typewriting, high-speed photography, and magnetic recording. A greater variety of data could thus be obtained than has hitherto been possible, and continuous recording over long periods of time would not be limited, as would be the case in actual flight. Several preliminary studies using motion picture techniques have been made to analyze aircrew duties on multi-engine aircraft.[6] Similar studies could be included in the procedure outlined above. The reactions of the crews under critical operating conditions could be more clearly understood and controlled.

Operational Aspects of Fatigue. Closely related to the complexity of aircrew duties is the equally important problem of operational fatigue. It is only natural, for example, for airmen to be more subject to error or to confuse one control with another if there is a reversal in position from one model to another. This confusion might be accentuated during the last three or four minutes of a long flight. Operations carried out in a Dehmel Trainer should provide an experimental approach to the role of fatigue in contributing to errors having design implications.

The concepts of skill fatigue developed by Bartlett and his associates provide an interesting hypothesis for fatigue and error in transport pilots.[7] They observed that the development of fatigue in the performance of a highly skilled task, such as flying, may involve various forms of disintegration if the airmen are pushed beyond certain limits. The deterioration of skill is characterized chiefly by an unwitting relaxation in the operator's standards of performance.

The principal objective signs of the onset of skill fatigue are as follows: (1) inaccurate timing of control movements, (2) a tendency to require excessively large changes of stimuli before action is produced, and (3) a lessening of the normal span of anticipation. In addition, certain subjective or clinical symptoms become evident. These were characterized by an enhanced awareness of bodily sensations, by an associated hyperreactivity and aggressiveness toward the machine and other people, and by projection of responsibility for known failures.

One of the most promising methods, therefore, for studying fatigue in pilots in relation to aircrew duties is a quantitative analysis of skill fatigue. It would be possible to test experimentally some of the factors indicated in the following quotation from Bartlett. "To fly any aircraft accurately and well, the pilot must be able to treat a complete field of events as one interconnected whole. In instrument flying, for example, all the instruments of

critical importance are treated as one. A glance at a movement over the dial face of any instrument is immediately and without special thought associated with the corresponding movement on the other instruments. Hence any such movement is interpreted in terms of what the aircraft is doing or is just going to do. But as the pilot becomes tired, the signals and the task split up. If a recording needle on a dial moves beyond the limits that are regarded as correct, it is that needle which must be corrected, even if the correction is made in such a way that something else is put out of place. The fresh pilot flies his aircraft. The tired pilot tries to control several different recording instruments, or to deal one by one with a number of different aspects of his total situation. So there will be much overcorrection and much undercorrection and a greater amount of fluctuation."[8]

The above experimental approach might be used to study many human variables in the design and operation of air transports. For example, it would be possible to show whether a two-man crew might experience more difficulties at the end of long flights than a three-man crew which includes a flight engineer. Furthermore, it would be possible to study the deterioration in skill relating to fatigue. Finally, much light could be thrown on the role of design in accentuating errors in the performance of various types of aircrew duties.

Many other illustrations could be given of the need for advance analysis of design factors in relation to human variables. For example, the studies of DeHaven have shown that, in many cases, seats have been stressed below the tolerances of the human body.[9] Furthermore, protruding objects on the instrument panels or the controls have given rise to high casualty rates. The head often strikes one of the protruding objects because the safety belt allows the body to pivot forward at the hips. It is reasonable to believe that shoulder harnesses would greatly improve the survival rates and that consideration should be given to this problem for aircrews on transport planes.

Many believed that the light plane industry and private flying would develop after the war because of the tremendous number of pilots being trained by the CAA training program and the services. During the five years, 1940 through 1944, 100,000 civilian and 300,000 Army and Navy men were trained to fly. It was undoubtedly assumed that a substantial proportion would continue flying and possibly buy a plane. This has not proved to be true, primarily because the planes are not fool-proof and efficient from the point of view of the human aspects of design, as is the motor car. Approximately one out of every 85 light planes is involved in a fatal accident each year, and most of these are attributed to pilot error.[10]

In summarizing the design implications of human factors, I should like to emphasize that the engineers have done an excellent job with the limited information available to them about human factors. Naturally, they build according to specifications provided for them, and in many instances they are blamed for errors that should be attributed to others. The physiologists and psychologists should provide adequate design criteria or limits of acceptability in order that the engineer may incorporate this knowledge into the original design of aircraft. Safety and comfort can be

greatly improved once the experimental basis for each of these variables is known.

Physical Standards and Requirements of the Job

In recent years, a great deal of confusion has existed with regard to standards of physical fitness for pilots in relation to the requirements of the job. There is disagreement not only as to the functions to be tested but also as to whether the standards should be more lenient. Those who argue for greater leniency point out the lack of relationship between the findings on medical examinations and accidents. The author's view in this matter is that a sounder basis of relating physical requirements to performance should be developed. In other words, after it has been clearly determined what a pilot is expected to see and hear or what physical stresses he may encounter, the tests and various other aspects of the physical examination should be directed toward these traits or functions. Furthermore, unless the equipment is designed to fit the operator, it will be necessary (1) to select exceptional individuals who can utilize the existing equipment or (2) to redesign the equipment to minimize the critical nature of selection standards.[11] A few examples from the field of vision and hearing will demonstrate the relationship of physical fitness to flight performance and to the design features of the equipment.

Vision at Night from the Cockpit. Interest in night vision has been stimulated in air transport operations by the necessity for night operations in all parts of the world. Many serious accidents in aviation have occurred at night. Incidentally, about 60 per cent of the traffic fatalities in the United States occur during dusk and darkness. If pilots could rely solely on instruments or on airport lighting systems, then adequate dark adaptation for vision outside the cockpit would be unimportant. Unfortunately, additional technological advances must be made before the necessity for dark adaptation can be eliminated.

The simplest way for a person to attain optimum night vision is to remain in the dark for approximately 30 minutes. Unfortunately, this is not practical in actual operations, and in an emergency the time lag necessary to achieve adequate night vision may be dangerous. Studies of the relative merits of light of different wave lengths for preadaptation have shown that if a person works under red light or wears red goggles there is a minimal stimulation of the rods. The relative insensitivity of the rods to light of wave lengths greater than 630 millimicrons permits the eye to achieve very nearly its maximum degree of dark adaptation if the over-all sensitivity is not too high. At the same time, the sensitivity of the cones to red light permits an individual to retain sufficient day vision to recognize details. The results of several experiments also indicate that an operator would reach a given level of night vision more rapidly if he had been working under red than under dim white light. If the pilot must see outside the plane at night, then a cockpit lighting system designed to facilitate dark adaptation, as indicated above, would appear to be advisable.

The installation of a red lighting system in the cockpit to facilitate night vision would naturally have implications for cartographers in the design

of maps which can be used under red as well as white light. Naturally, the red lines on a map are not visible while looking at them in the presence of red light or through red lenses. Furthermore, the requirements for color perception should also be considered in relation to the colors used on the maps. The Loran chart, for example, has four colors, namely, violet, amber, green, and blue. These colors may readily be confused in poor lighting or by airmen with poor color vision. Also, a shade of the same color may differ considerably as between one map and another. Although there may be many difficulties in the way of standardizing the choice and shades of colors, the designers of the lighting system in the cockpit, the maps to be used en route, and the selection standards for color perception should all be considered in the design of equipment. No better illustration can be

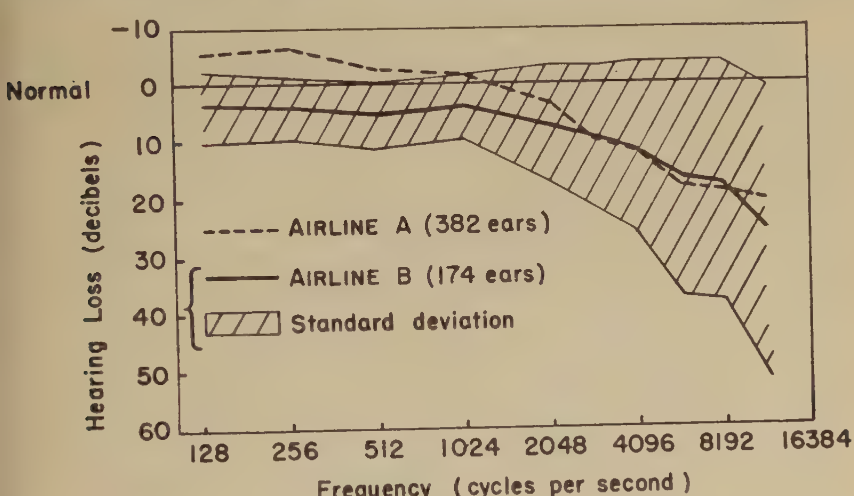

FIGURE 1.

given of the need for integrating (1) design of equipment, (2) operating practices, and (3) the selection of personnel.

Hearing Standards for Pilots. Several considerations should be kept in mind in establishing physical standards of hearing and in designing auditory aids for crewmen in flight. One factor relates to the pilots with auditory defects. A second relates to the requirements of the job, or what signals must be heard during flight, and the third to the design of equipment in relation to the hearing losses which are most common among pilots, especially those in the older age group. Relevant data on each of these aspects of hearing requirements for airline pilots will be summarized briefly.

With regard to hearing losses, audiograms were obtained for two groups of airline pilots, and the mean curves and standard deviations are shown in FIGURE 1.[12, 13] Many of the pilots show a considerable loss in the higher frequencies, and obviously many would be disqualified if rigid standards were applied. The effect of various cut-off points on the present airline

pilot personnel is shown in TABLE 2. The first four columns in the table indicate the cut-off point in decibels at each of four test frequencies. In Criteria I and II, 4096 cps was eliminated as a test frequency. The data indicate quite clearly that this particular test frequency is a very critical one in influencing the number that would be eliminated. If Criteria II and III were applied to individual ears, approximately the same percentage of the airline pilot sample represented in this table would be eliminated. If 4096 cps is included as a test frequency, the percentage eliminated will increase very rapidly as the cut-off point is lowered in terms of maximum permissible loss. In the case of the left ear, for example, changing the cut-off point from 40 db to 20 db means that the percentage of eliminees will be more than tripled, *i.e.*, 22.2 per cent instead of 6.6 per cent.

TABLE 2
INFLUENCE OF VARIOUS CUT-OFF POINTS ON DISQUALIFICATION RATES ON 608 AIRLINE PILOTS

Criteria for disqualification	*Basis for disqualification Maximum permissible losses in db at selected test frequencies**					*Failed in left ear*		*Failed in right ear*		*Failed in both ears*	
	512	*1024*	*2048*	*2896*	*4096*	*N*	*%*	*N*	*%*	*N*	*%*
I	30	30	30	—	—	15	2.5	18	3.0	6	1.0
II	20	20	20	—	—	42	6.9	37	6.1	16	2.6
III	40	40	40	—	40	40	6.6	43	7.1	27	4.4
IV	30	30	30	—	40	44	7.2	49	8.0	29	4.8
V	30	30	30	—	30	68	11.2	75	12.3	42	6.9
VI†	20	20	20	30	—	64	11.6	58	10.5	31	5.6
VII†	20	20	20	25	—	75	13.5	71	12.8	40	7.2
VIII†	20	20	20	20	—	96	17.3	90	16.2	55	9.9
IX	20	20	20	—	20	135	22.2	116	19.1	81	13.3

* Test frequency of 256 cps was not included in criteria because losses of more than 20 db were found in less than 1 per cent of all ears examined. Only three additional ears, involving three pilots, would have been disqualified on the basis of a strict standard of 20 db maximum loss of 256 cps.
† Based on 554 cases for whom losses at 2896 cps were available.

Equally important is the functional relationship of these standards to the task of aircraft piloting. It is necessary first of all to determine the critical frequencies. To hear the human voice and the most frequently used signals, good hearing is required in the frequency range of about 500 to 3,000 cps. The four-course radio range or radio beam is the chief signal and is operated at 1,020 cps. The important voice frequencies range up to about 2,500 cps. Beyond this point, the only frequency which must be heard is 3,000 cps, the highest of three frequencies used for fan and cone markers. In this connection, it should be noted that these markers give a visual signal on the panel as well as an aural signal. It is therefore apparent that test frequencies of 512, 1024, 2048, and 2896 would give a satisfactory frequency range over which the pilot's hearing should be measured.

Another consideration is the extent to which signal amplification can be used to offset hearing losses. Such amplification is feasible only within certain limits. For example, if the volume control for the radio beam is increased by an excessive amount, the receiver will no longer differentiate

the A and N signals. Normal pilots frequently listen to this signal at a headphone intensity of only a few milliwatts. One with a 30 db hearing loss at this frequency might require about 1 watt amplification, an intensity level leading to distortion and possible misinterpretation of the signal. Similarly, at 3,000 cps, a loss of more than 25 db might mean that the aura signal would not be heard. The signal also operates a panel light, however, which would probably be seen. In so far as design of equipment is concerned, it would be desirable to introduce new signal frequencies within the ranges which can be most easily heard by a majority of the pilots.

In the interest of safety, a standard of 20 db maximum permissible loss at 512, 1024, and 2948 cps and of 25 db at 2896 would seem to be satisfactory. This criterion actually corresponds to VII in TABLE 2. This would disqualify about 13.5 per cent of the present airline population on the basis of the sample if rigidly applied.

In the case of older, more experienced pilots, some leniency should be permitted. This is particularly true since those with a hearing loss have more normal hearing in the presence of noise on the aircraft. This is a result of the "recruitment" phenomenon in their hearing. The principal reason is that low intensity signals are masked. In fact, for very loud intensities, the person with marked hearing losses as measured by the audiometer may actually hear quite well. Older pilots with hearing losses therefore should be tested in simulated aircraft noise. If the hearing losses do not interfere with intelligibility of normal conversation safety would not be compromised. The ICAO Hearing Requirements as recently modified for airline transport pilots take this factor into account in that a practical test on the aircraft is allowed. This is fairer to the pilot and relates the test to the performance of his duties.[14]

Design of Equipment and Operating Procedures

In addition to designing equipment to fit the operator and relating physical standards to the requirements of the job, it is necessary to consider the design of equipment as it relates to operating procedures. The newer features in the design of air transports have raised many interesting questions relating to the indoctrination of personnel in the safe and efficient use of such equipment. Two examples will be taken from contemporary operating experience. The first relates to the effects of carbon monoxide at high altitude and the second to explosive decompression.

Effects of Carbon Monoxide at High Altitude. Differences of opinion have arisen among the manufacturers, the military services, and the airline operators in regard to the permissible limits of carbon monoxide on aircraft. The problem is more serious on military aircraft than on air transports. In high speed military aircraft, using internal combustion engines which are located in front of the pilot, it is very difficult to prevent the entry of carbon monoxide into the cockpit. On air transports, with the engines located on the wings, there is less likelihood that carbon monoxide will enter the cabin. There are, however, other sources of this gas, such as internal combustion heaters located inside the cabins. The most satisfactory solution of permissible limits for carbon monoxide can be worked out only by relating

the effects of various amounts of this gas not only at sea level but also at an altitude.

The author and his colleagues were asked by the Lockheed Aircraft Corporation to develop an objective criterion of the functional changes from carbon monoxide poisoning in aviation.[15] Studies were made both at sea level and at various altitudes. Criteria for the permissible limits were established by means of a test of light sensitivity and also the amount of carbon monoxide in the blood. Light sensitivity was chosen as the index because previous experiments had shown it to be very sensitive to the effects of low oxygen tensions. In addition, the test is objective, and the subject, being unaware of the quality of his performance, cannot compensate. The effects of carbon monoxide on visual thresholds were correlated with those of anoxia. By means of the concept of physiological altitude, it was possible to arrive at a definition of the concentrations which might prove hazardous to a pilot because of the effect on his visual performance. From a practical point of view, it was found that when carbon monoxide is absorbed at high altitude, where the individual is already anoxic, the effect of the added percentage of carboxyhemoglobin is the same as the effect of an equal additional loss in percentage of oxyhemoglobin. Thus the pilot's physiological altitude is considerably increased by carbon monoxide over the true (pressure) altitude at which he is flying. For example, with 0.005 per cent carbon monoxide in the atmosphere at 9,000 ft., the physiological altitude of the pilot is about 15,000 ft.

On the basis of safety, it was concluded that a limit of 0.003 per cent carbon monoxide is more desirable than the usual standard of 0.005 per cent for long-range operations during which small amounts of carbon monoxide may have nearly maximum effects. These standards are based primarily on the welfare of the aircrews rather than the passengers, since the amounts are not sufficient to jeopardize the health of the latter. The safety of the air transport may be endangered during such critical periods as in night flying, however, where vision is already handicapped. This reasoning and method are also applicable to the determination of critical standards for truck cabs or other situations where the visual performance of the operator may become a limiting factor.

If the pilot suspects the presence of carbon monoxide or any other atmospheric contaminants, such as excessive amounts of carbon dioxide, he should be indoctrinated to don his oxygen mask. This latter procedure might have prevented several accidents in 1948 in which excessive amounts of carbon dioxide, *i.e.*, approximately 20 per cent and higher, accumulated in the cockpits of pressurized planes using carbon dioxide fire extinguishers within the pressurized areas.

Operating Experience with Pressurized Aircraft. As so frequently happens, the solution of one problem only tends to create another. In this instance, it relates to the possibility of a sudden loss of pressure during flight. For example, if a transport is flying at 21,000 ft. true altitude with a cabin pressure of 7,000 ft., what harmful effects might be expected to occur to the passengers?

There are at least four important physical variables which must be considered in the event of an explosive decompression: (1) the volume of the pressurized compartment, (2) the size of the opening, (3) the pressure differential, and (4) the flight altitude at which decompression takes place. Naturally, the most drastic decompression possible would be that occurring in the smallest cabin with the lowest cabin altitude at the highest possible flight altitude. Experiments have been made at Wright Field to test the very extreme conditions mentioned above for military aircraft in flight at 35,000 to 40,000 ft. The results indicated that the average subject experienced a sense of inflation in the chest and abdomen as a result of expanded gas, and about 20 per cent of them suffered bends during the first 5 minutes at altitude.[16]

If an astrodome, door, or window fails in the fuselage of a transport at 21,000 ft. with a cabin pressure of 7,000 ft., the plane should be able to descend rapidly to a safe altitude. Numerous tests have shown that a transport flying at 23,000 to 25,000 ft. can descend to about 14,000 ft. in three to four minutes. The major difficulty would be the acute oxygen want that would result if the plane were unable to descend because of weather or terrain and if oxygen were not available for each person aboard the aircraft. Such a combination of circumstances, however, is unlikely and has not thus far been encountered on any of the explosive decompressions in commercial air transportation. In each case of which the author is aware, the plane has been able to begin an immediate descent, reaching safe altitudes within six to eight minutes. For example, on October 20, 1946, an astrodome failed on an air transport during a transatlantic flight. The plane began an immediate descent from 21,000 ft. and reached 7,000 ft. in less than ten minutes. On March 10, 1947, another astrodome failed. Unfortunately, the navigator was sucked out of the astrodome. The crew and passengers reported no unusual symptoms, however, and the pilot reduced altitude at a rate of 700 ft. per minute, leveling off at 10,000 ft.

The provision of supplementary oxygen on pressurized aircraft remains a controversial subject. If an emergency supply of oxygen adequate for all passengers for 30 minutes or more were required under present operating conditions, there would be a considerable weight penalty, and passengers would have to be routinely indoctrinated in its use. Also, it is unlikely that the flight crews could assist passengers in donning their masks during the time when it would be most useful, *i.e.*, before descents to safe altitude could be made. Others point out that a built-in oxygen system with individual outlets at each seat should be provided in case the airplane cannot descend to low altitudes because of mountainous areas or extremes of weather and icing. Furthermore, since it would be difficult to move passengers from one seat to another, individual outlets or portable equipment would be a necessity. It has been pointed out further that oral-nasal masks should be provided, because inexperienced persons would be apt to lose consciousness with the nasal type of mask while talking at altitudes above 25,000 ft. Thus far, operating experience at 25,000 ft. and

below suggests that a supplementary supply of oxygen for passengers is unnecessary. Above such altitudes, however, there seems to be general agreement that emergency oxygen for all passengers must be available.

Conclusion

The main thesis presented in this discussion has been that improvements in safety and efficiency in airline operations center around the design of equipment to comply with the human characteristics of the operators. Working areas in the cockpit and the equipment to be used in flight should be built around the limitations of the aircrews rather than merely attempting to fit them in without an advance analysis of their abilities and what is expected of them. Failure to consider the human implications in the original design necessitates (1) costly modifications after the planes are put into service, (2) the selection of pilots with superior ability to meet the exacting demands of the job, and (3) longer training periods to provide wider margins of safety during actual operations.

Bibliography

1. McFarland, R. A. & A. H. Holway. 1941–42. Visual problems in fire control. Research Project No. 10, NDRC.
2. McFarland, R. A. 1946. Human Factors in Air Transport Design. McGraw-Hill. New York.
3. Fitts, P. M. & R. E. Jones. 1947. Analysis of factors contributing to 460 "pilot-error" experiences in operating aircraft controls. AAF Rept. TSEAA-694-12, Engineering Division, Air Materiel Command, Wright Field, Dayton, Ohio.
4. Gordon, T. 1947. The airline pilot: a survey of the critical requirements of his job and of pilot evaluation and selection procedures. Rept. No. 73, Division of Research, Civil Aeronautics Administration, Washington, D. C.
5. Adams, C. 1948. Third crewman: flight engineer. Aviat. Week **48** (16): 38.
6. Channell, R. C. 1947. An analysis of pilot's performances in multi-engine aircraft. Project No. 20-0-1, Special Devices Center, Sands Point, L. I., N. Y., Office of Naval Research, Department of the Navy.
7. Bartlett, F. C. 1943. Fatigue following highly skilled work. Proc. Royal Soc., Biological Series B **131**: 247.
8. Bartlett, F. C. 1942. Fatigue in the air pilot. Rept. 488, Flying Personnel Research Committee.
9. DeHaven, H. 1944. Mechanics of injury under force conditions. Mech. Eng. **66** (4): 264–268.
10. Lederer, J. 1948. Loss prevention programs in civil aviation. Aeronaut. Eng. Review **7** (7): 25–32.
11. McFarland, R. A. 1950. Human Factors in Airline Operation. A study of occupational health and safety. McGraw-Hill. New York.
12. Graebner, H. 1947. Auditory deterioration in airline pilots. J. Aviat. Med. **18** (1): 39–47.
13. McFarland, R. A., A. Graybiel, E. Liljencrantz, & A. D. Tuttle. 1939. An analysis of the physiological and psychological characteristics of two hundred civil air line pilots. J. Aviat. Med. **10** (4): 160–210.
14. Final Report. 1948. Personnel Licensing Division, Third Session, Montreal, Canada, International Civil Aviation Organization, 30 March to 23 April.
15. McFarland, R. A., F. J. W. Roughton, M. H. Halperin, & J. I. Niven. 1944. The effects of carbon monoxide and altitude on visual thresholds. J. Aviat. Med. **15** (6): 381–394.
16. Sweeney, H. M. 1947. Explosive decompression. Trans. 35th National Safety Congress. **4**, Air Transport Section, Chicago, National Safety Council.

SOME CONSIDERATIONS OF AEROMEDICAL RESEARCH

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War, for all its malignancy and degradation, for all its chaos and tragic waste, makes one single and solitary contribution to the progress of mankind—albeit never sufficient to redeem or justify itself. This contribution lies in its effectiveness in pushing forward the frontiers of knowledge at a faster rate than during peace.

This artificial stimulation of progress as an accessory to war has obtained in so many different fields of human endeavor that a certain school of thought in the days of our languishing peace from the end of one war to the beginning of the last did attempt to justify war as an acceptable means to an end—namely, progress. Few, I dare say, in these days of spiritual and international crisis, however, can regard such an attitude with anything but revulsion.

Nevertheless, war does serve to integrate the research programs of allied and diversified sciences. Its successful outcome requires that maximum endeavor, and hence most effective organization, be assured. The emotional investment of a nation under threat of defeat serves to unite the greatest output of effort in order to achieve success. Scientific progress tends to enhance the likelihood of victory by an amount proportionate to its superiority over the enemy's scientific progress.

War, therefore, stands out conspicuously as the one unique example of a force so universally effective upon a people as to result in integrating an automatically oriented program of research.

During peace, a state to which few of us have been exposed in its true form, few of these integrating forces develop. They fail to appear because there is little apparent need, and because a democratic state cherishes the tenet that individual freedom of thought and action must be maximized, consistent with certain necessary prohibitions for the good of the state. This latitude of action and diversity of interest is healthy from the angle of pure science, but in terms of meaningful objectives it inevitably achieves the greatest possible dilution of talent and money. In comparison with the significance of progress under a war-oriented research program, the results of poorly disciplined peacetime research appear far less meaningful than they merit, even from the purely academic viewpoint. Attempts to establish a broadly unified and integrated program of research in peacetime, or even such a period in history as the present, usually meet with apathy. This situation stems directly from the fact that totally different philosophies guide the wartime, as distinct from the peacetime, program. The former is oriented around the premise that the state shall not perish, (and with it, the individual), while the latter holds primarily that the individual's rights shall not be abrogated.

Is this sound and realistic? I cannot find it so. In our experience, and we should learn from it, peace, for all nations but our own, appears to be

merely a period of preparation for war—either aggressive or defensive. Potential enemies obviously prepare for aggressive war and assume as a right of the state, and a prerequisite to war preparation, the mobilization of as much of its internal resources as it can spare from its economy. When war is brought to us, the record of history shows that we characteristically accept the urgency of national defense and, as quickly as we can, become a near-militaristic nation—fully as dedicated to victory as our enemies, if not more so. We reorganize our economy, we expand our nucleus Army, Navy, and Air Force, we gear up our industrial potential, we regiment and organize our population, and, in research, we rouse from contemplative lassitude to extreme activity, passing through various phases of development with severe growing pains and adolescent awkwardness, finally to reach a realistic and mature stature. All this we do in what has become an increasingly difficult effort to catch up with the progress made by an enemy during the years of war preparation.

Whether we can ever again succeed in a "catch-up" race is a very debatable question.

If we can accept the full meaning of war when it explodes on our horizon, we should be able to comprehend the vital importance of initiating and maintaining a scientific potential superior to that of our strongest potential enemy, and this requires preparation long before its probable need. Aesop's fable about the tortoise and the hare can be here recollected with profit if we recall that steady continuous progress reaches its goal ahead of furious but sporadic periods of endeavor.

As the only piece of war potential of which I can speak with any authority, scientific research appears to be a component that will not lend itself to a program of discontinuity. During the last conflict, it was exceedingly slow in getting started, and, after four years of war, orientation had only just begun to mature. It should be obvious that our zone of leeway for another war, with its severely reduced dimensions of time and distance, has shrunk to proportions that almost eliminate it from consideration. At the onset of war, research data will be needed "as of yesterday."

As a consequence of recognizing these facts, what then becomes our obligation as scientists? We can probably do little anywhere but in our own fields. We can probably do no more than set our own house right and then verbalize our beliefs at every opportunity. Probably our greatest task in the housecleaning we must undertake arises from the fact that if we, as both scientists and mortal human beings, are to survive, we cannot condone unplanned, unoriented, or casual research, or operate under such conditions. We must establish independently a clearly planned, well-conceived research program and impose it upon ourselves. We must have as the main objective of our program the very survival of man—of which we, in our own eyes, are very important examples.

If research, in the many diversified fields which affect the survival of man, is oriented toward that objective, scientists will have accomplished all that lies within their power. Further guarantees can be underwritten

only by similar efforts among the military, diplomats, and politicians, supported by the great American community.

Research in the past has traditionally been associated with academic life, free of compromise by profit-seeking business and industry. Academicians sheltered in an ivory tower theoretically have dwelt and worked so far from the "madding crowd" as to be immune to criticisms of prejudice, selfishness, and other altogether human motives of self-aggrandizement. These legends have been necessary for research to be regarded as "pure." In order to maintain the purity of research and, hence, its authoritative prestige, a system has been developed for conducting research with military applications. This system operates through government-sponsored research, conducted not in government or military laboratories, but in universities and foundations. Planning and coordination of results thus become channelized under headings not blatantly military, but pointed toward national security. Two valuable purposes are achieved through this sort of program; namely, the continued effectiveness of important research agencies and the initiation of broad research programs starting at the level of pointed basic research, or research aimed at a particular ultimate application.

This system is undoubtedly more effective than the relatively uncoordinated activity we knew before the last war, wherein research was synonymous with miscellany. Dilution of effort resulted from research guided primarily by personal interests. Voluminous reports made a difficult task of library research into a particular subject. Bibliographies contained an abundance of irrelevant material.

Medical research has throughout the war, and since, probably been less affected by any of the coordinating research plans than other branches of science. Orthodoxy legislates it; convention polices it; and the medical fraternity adjudicates it. Special privilege and freedom from regimentation accrue to the medical branch probably as a sociological vestige of the primitive medicine man's tribal position and, naturally, the imposition of outside authority is resisted. Witness the medical attitude toward socialized medicine, both at home and abroad.

During the war, however, medical personnel and representatives of the allied services did achieve a joint effort wherein individual laboratories and foundations coordinated their programs and aimed at the common objective of victory. Coordination took place in various committees, mostly under the auspices of the National Research Council and the Office of Scientific Research and Development. Fortunately, not all of that potential coordinating power has disappeared, in spite of the fact that its effectiveness has deteriorated as a sequel to victory.

Two significant committees still function, largely because of the character of their membership. These committees, the Vision Committee and the Committee on Aviation Medicine, have refused to recognize that the time of crisis has passed and are trying to hold the ground that was gained during the war when coordination was their chartered right.

The membership of these committees stands as one of the few monuments to the discovery that research coordination requires team organization. In medical research, it was learned that research teams gained in effectiveness if oriented around the central theme of function and/or performance.

We learned, for example, that a problem relating to the use of binoculars for night lookouts—typical of many of the visual problems encountered during the war—could not be wholly solved by an ophthalmologist, nor by an optical physicist. A team such as that brought together by the Vision Committee could approach the problem, break it into the components of physiology, psychology, physical optics, statistics, and military requirements, and, collating the simultaneously collected data, produce a speedy answer.

In aviation medicine, not of itself a conventional specialty but rather an amalgam of special aspects of general medical subjects related to the problems of flight, this team cooperation became vital in research. Medical personnel, primarily Flight Surgeons, soon learned that Jacks-of-all-trades, such as they were, could not hope to solve single-handedly the often abstruse problems thrust upon them by war. Scholars and academicians in pertinent fields had to be recruited to light the dark corners of the inevitable ignorance of the Flight Surgeons. The Navy Medical Department, accordingly, allied itself closely with various specialists, particularly psychologists, and enjoyed a profitable symbiosis. Under these conditions, aviation medicine progressed rapidly and rose in prestige, contributing significantly to pilot selection and training and to increasing both pilot effectiveness and safety. Flight Surgeons, almost without realization, had constructed teams whose research efforts were not oriented around the physiology or the endocrinology of a piece of a man, but about the total function of the whole human organism, equilibrium, hearing, vision, discrimination and judgment, G-tolerance, and many others.

With engineering refinements producing aircraft of increasing performance, aviation medicine early realized that human tolerances could be exceeded in flight, and that, hence, man himself imposed certain restrictions on aircraft performance. Tactically, military power resulted from air power, and air power in many ways was limited by aviator performance, imposing thereby a tremendous military obligation on the aeromedical team to extend the range of aviator performance.

Much of this obligation was fulfilled through well-planned and executed aeromedical research, but the progress came to an abrupt halt with rapid demobilization. Aeromedical research teams broke up and were scattered, but a philosophical concept remained.

From the remnant emerged a concept that should probably have been formulated earlier in the scheme of things, human engineering. A satisfactory definition of the term, for this purpose, is that it embraces the study and application of physiology, psychology, medicine, and anatomy as they affect the relationship between men and machines. Applied to aviation medicine, this refers primarily to the pilot-plane relationship.

This concept did not spring from the body of medical personnel but

rather from a research teammate, the psychologist. As is true with all good things, an effort has been made to claim prior right to its cognizance by different groups, and a certain amount of effort has been made to "return it to the fold." Realistically speaking, however, it is improbable that medical research would, or could, assume prudent responsibility for all aspects of human engineering. Certain it is, though, that some particular aspects should come within the purview of aeromedical research and, probably, industrial medical research. No brief can be held by medical research against the case for divided but closely related responsibility for other aspects of human engineering. Such divided cognizance requires resumption of the symbiotic relationship if progress in research is to be assured.

Many of us in aeromedical research have recognized the merit of human engineering as a matrix within which to orient our programs, yet we have accepted it almost tacitly and, perhaps, subconsciously. This undoubtedly derives from the fact that psycho-physiology undertook the greater part of its postwar activity—at least on the level of applied research—under the human engineering label. Use of the label by other groups, therefore, might perhaps have compromised either their prestige or autonomy, or both. Reluctance, then, to identify aeromedical research with human engineering can be more or less understood.

We stand today on the threshold of a new air age: the age of supersonic flight. How we answer the challenge will determine whether or not we shall cross this threshold, and, perhaps, whether or not we can survive as a nation. This particular crisis is with us and has been with us for months purely because aeromedical research has been outstripped by aeronautical achievement and inevitably has been slow to produce the desperately needed answers. Whether or not an aeromedical research program organized within human engineering disciplines would or would not have prevented this hiatus is definitely beside the point. All that can be done now is to look ahead.

Supersonic flight not only imposes aeromedical problems of the first order of magnitude, but also imposes additional problems which can be completely embraced only by a human engineering consideration of the man-machine or pilot-plane relationship. Organized military aeromedical programs, as they stand today, therefore, do not completely fulfill both of the above research requirements of supersonic flight. How they fall short of the need will appear after a brief consideration of the major problems of manned supersonic flight.

By-passing the very significant aerodynamics attendant upon supersonic flight, we must, because of the limitations of space, turn directly to the major problems of the aviator in the supersonic cockpit. We classify them as follows: (a) the acceleration environment, (b) visual performance, (c) thermal surround, (d) ultrasonic environment, and (e) pilot escape. We are concerned, under the above classifications, with the outer limits of human tolerance consistent with the basic mission of aviation medicine to enhance the aviator's effectiveness, increase his safety, and provide for his comfort.

A consideration of the acceleration environment indicates that one of the first and, perhaps, the most important obstacle to supersonic flight may be high-frequency vertical acceleration, or vibration, in the order of four or five "G"—expected in the transonic range from Mach. no. 0.8 to 1.3. The solution to this may lie in passing through this critical velocity range as quickly as possible with special power reserve and in providing some kind of floating or damping mount for the pilot and instruments. Engine failure, which with reaction type power plants is abrupt, may impose longitudinal negative acceleration calculated as high as 20 G—as high a value as often determined in fatal crashes.

From the point of view of the pilot's visual contact with the outside, aviation medicine is concerned also with the potential problem of visibility through an oblique shock wave and heat boundary layer. The research tools required to explore this problem are, however, not so much aeromedical as aerodynamic. In this same connection, visual performance may be further restricted by structural vibrations with frequencies near the natural resonance of the eye itself. The significance of this phenomenon, if it occurs, needs no expansion.

In considering the thermal environment, large heat gains are known to exist, even in transonic flight. As functions of the energy conversions during shockwave formation and the boundary layer heat transfer coefficients, it has been calculated that skin temperatures of an aircraft may rise as high as 170° F. Low humidity and high volume exchange afford a limited means of reducing effective temperature, but heat gain of this magnitude, coupled with the effects of solar radiation, will undoubtedly require control by insulation and refrigeration—tailored to the environmental requirements of the human occupant. A clear delineation of those requirements has not yet been achieved.

Another problem associated with supersonic flight may develop as a consequence of the same energy conversions and, therefore, merits investigation. The problem is, in brief, two-fold: (a) Will ultrasound, *i.e.*, frequencies above 20 kc, develop as a result of supersonic speed? and (b) if it develops, will it be a biological hazard? Some evidence exists in the data collected from past high-speed flights near the transonic range to indicate that this phenomenon may occur as a by-product of high-frequency aerodynamic noise. Whether or not the natural frequency of an aircraft, or various individual components, will support resonance and transmission to the cockpit is a question in the realm of pure conjecture. Whether ultrasound is biologically deleterious or at what energy levels it may or may not be tolerated, are questions that science has not yet answered. Various accidental exposures followed by deleterious results, reported in the literature, have been traced to their source and found to be more or less anecdotal gossip—wholly without substantiation.

Last but not least is the still unsolved problem of aviator escape at high speeds and high altitudes. The probable maximum velocity at which a pilot may safely use an ejection seat is about 500 miles per hour. When high deceleration forces occur, as they will with failure of a jet aircraft traveling at high velocity, the first emergency will be protection of the

pilot. A slower rate of deceleration will be required and this appears possible only by providing some sort of a jettisonable cockpit with an independent emergency power plant to permit continuation of the line of flight at a more slowly decelerating velocity. Superimpose upon this aspect the further possibility that the failure may occur at sixty to eighty thousand feet and the aviator, then, will obviously have to be provided with independent pressurization for the jettisoned cockpit. Furthermore, pressurization at the greater pressure differentials required for such high altitude operations so greatly increases the hazards of explosive decompression as to require absolutely that the whole sequence of jettisoning and release operation be completely automatic, since the consciousness of the pilot cannot be guaranteed.

With this admittedly sketchy résumé of the uncertainties surrounding piloted supersonic flight, it is illuminating to consider in what fields research programs are required for just the first basic answers. It is unfortunate that a detailed analysis of the research contributions cannot be outlined, but it is, at the same time, obvious that such an outline would seriously compromise security classifications. Little more can be said than that some of the preliminary working data pertaining to supersonic flight must be supplied by aerodynamics, optical physics, geophysics, ordnance, ballistics, mechanical and aeronautical engineering, and with the coordination of the aviation medicine specialties of physiology, psychology, otolaryngology, ophthalmology, and internal medicine.

It becomes obvious that the problem of supersonic flight, a subject of the greatest concern to aviation medicine, and probably one of its gravest responsibilities, cannot be solved by aviation medicine alone. The coordinated efforts of the special fields outlined above, however, do embrace most of the problem if the body of research rests upon considerations for the man-machine relationship, or the principles of human engineering.

The Special Devices Center, of the Office of Naval Research, conducts its research programs, and, in particular, the program of the Flight Section, with the fullest appreciation of the man-machine relationship. No potential contribution of the least likely branch of science is ignored in the coordinated integration which is the Special Devices Center's constant matrix for the pursuit of human engineering objectives.

I regret that security classifications prevent my describing in detail the manner in which the Special Devices Center implements within the structure of the Flight Research Program the fullest understanding of human engineering principles.

Even as the significance of these principles has been demonstrated for the fuller function of aeromedical research, so it must also appear of corresponding importance when applied to other sciences.

Man, with the aid of science, has created a world of machines, but stands bewildered by his creation. Until he understands fully the relationship between himself and the machines, he is as likely to be destroyed by them as to be carried forward to a richer life. Our part, as flight surgeons, in assuring the continued survival of this nation, therefore, would clearly appear to be the reorientation of our research program around the broadest interpretations of human engineering principles.

HUMAN EFFICIENCY AS A FUNCTION OF LIGHT AND ILLUMINATION

By Henry H. Hausner

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There is hardly any other range in the spectrum of electro-magnetic waves which affects life as much as the radiation between 0.36 and 0.76 microns, which we call light radiation. Light itself is a human sensation caused by the effect of light radiation on the retina of the human eye. Light, according to the definition of the Illumination Engineering Society and the American Standards Association, is "radiant energy evaluated to its capacity to produce visual sensation." Illumination engineering is the art to produce and control light radiation with the purpose of creating better seeing conditions. Thus, illumination engineering is an essential part of the field which we call human engineering.

A few decades ago, illumination was merely an art and was hardly considered a factor contributing to human efficiency, comfort, and welfare. With the development of the incandescent lamp, however, illumination became an engineering technique. The necessity for good illumination was recognized, and new ways for controlling light radiation were found. At present, illumination engineering is in a state of transition. The art which became an engineering technique is developing into a science, comprising physics, physiology, and psychology.

The physiological and psychological effect of light, and a certain correlation between light and human efficiency, are shown, in a very general way, in FIGURE 1. This diagrammatic view of the field of illumination engineering shows that several physiological factors are involved in illumination, such as visual efficiency, eye-strain, eye fatigue, and, particularly, the ease of seeing, which affects the human efficiency in a similar way, much as do certain psychological factors, such as distraction, impression, annoyance, concentration, stimulation, *etc.* The complexity of illumination engineering may best be characterized by the fact that the latest developments in this field are described by engineers in journals of physiology and psychology, and by physiologists and psychologists in the respective journals of physics and illumination. The specialist on illumination, therefore, is either an engineer with a physiological or psychological background, or a psycho-physiologist with an engineering background. The close correlation between the engineering and the psychological aspects is further shown in occasional, though not necessarily fruitful, controversies between psychologists and engineers.[13]

Several years ago, when illumination engineering was still in the state of a technique, I investigated the effect of illumination on the speed of typewriting. Typewriting itself is a complex performance consisting of reading shorthand notes and writing at the same time. The tests were made with several well-trained stenographers, and the illumination was changed in a

predetermined way, the illumination intensity gradually increasing from 3 to 20 foot-candles, with uniform illumination intensity on the manuscript and the typewriter eliminating any annoying or disturbing glare. The shorthand notes were written with a "hard" pencil (No. 3). FIGURE 2 shows the average number of syllables written per unit time at various illumination levels. It shows that the speed of typewriting increases with increasing illumination intensity up to a maximum value. By changing the illumination from 3 to 20 foot-candles, the average increase in writing speed was 23 per cent. However, the speed of reading the shorthand and, consequently,

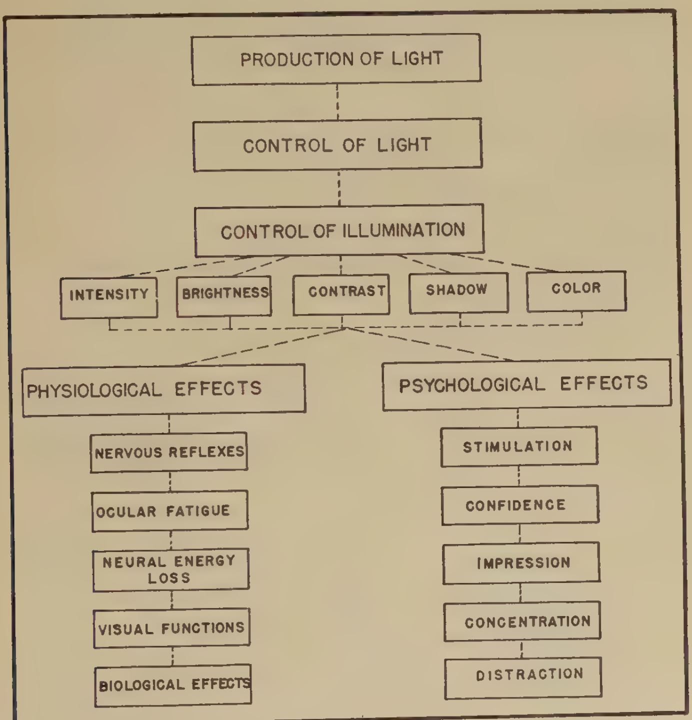

FIGURE 1. Physiological and psychological effects of light and light illumination.

the typing speed, was quite different when the shorthand notes were written with a "soft" pencil (No. $1\frac{5}{8}$). In this case, the brightness contrast between the white paper and the black shorthand notes was greatly increased, and reading was, therefore, much easier. The typing speed increased 20 per cent at a 6 foot-candle illumination level, while at an illumination of 20 foot-candles there was a still further 10 per cent increase.

In the course of further experiments, an unprotected incandescent lamp as the light source was used in such a way that part of the light radiation went directly into the visual field of the retina of the operator's eyes, causing a discomfort glare which very much annoyed the test persons. The typing speed, therefore, instantly dropped 17 per cent, and, after a few minutes, it

decreased 20 per cent. Some test persons complained of headaches, and the test had to be interrupted.

These tests, although not permitting general conclusions, decidedly show the effect of illumination intensity, brightness contrast, and glare on human efficiency.

Several years have passed since these experiments were carried out, and illumination engineering has advanced considerably since that time. Then, glare was just defined as "discomfort brightness." Today, we are in a better position to define glare and to predetermine under what conditions

	ILLUMINATION IN FOOT-CANDLES				
	3	4	6	10	20
SYLABLES PER UNIT TIME	61	66	72	74	75
PER CENT INCREASE IN WRITING SPEED	100	109	118	121.5	123

EFFECT OF ILLUMINATION ON TYPING SPEED (HARD PENCIL (NO. 3) USED FOR STENO.)

BY USING A SOFT, NO. 1$\frac{5}{8}$, PENCIL FOR THE STENO.
TYPING SPEED INCREASED
20 PER CENT AT 6 Ft. C.
10 PER CENT AT 20 Ft. C.

EFFECTS OF BRIGHTNESS CONTRAST ON TYPING SPEED.

DIRECT GLARE FROM UNPROTECTED 40-WATT INCANDESCENT LAMP DECREASED TYPING SPEED.
FOR 17 PER CENT AVERAGE IMMEDIATELY
FOR 20 PER CENT AFTER A FEW MINUTES

EFFECTS OF GLARE ON TYPING SPEED.

FIGURE 2. Effect of illumination, glare, and brightness contrast on typing speed.

brightness will create discomfort glare.[6,7] We know that discomfort glare not only depends on the glare source,[3] but on the respective state of adaptation of the human eye as well, and we determine the maximum comfort brightness B_g as a function of the initial brightness B_a to which the eye was adapted, and of the solid angle subtended by the brightness source.

$$B_g = \frac{K_1 \cdot B_a^{0,3}}{w^{0,25}} \tag{1}$$

For the evaluation of glare ratings, the glare factor K was developed:

$$K = \frac{A \cdot B^2}{D^2 \cdot \theta^2 \cdot S^{0.6}} \tag{2}$$

in which A = apparent area of light source (sq. in.), B = brightness of source $\frac{(\text{ft.}-\text{l})}{1{,}000}$, D = distance from source to eye $\frac{(\text{ft.})}{10}$, θ = angle between horizontal and line from above it from eye to source (degrees), and S = brightness of surrounding $\frac{(\text{ft.}-\text{l})}{10}$.

However, some confusion existed with regard to thinking on brightness,[11] resulting from the fact that there were too many terms and that these were predicated on theoretical assumptions. The confusion not only regarded

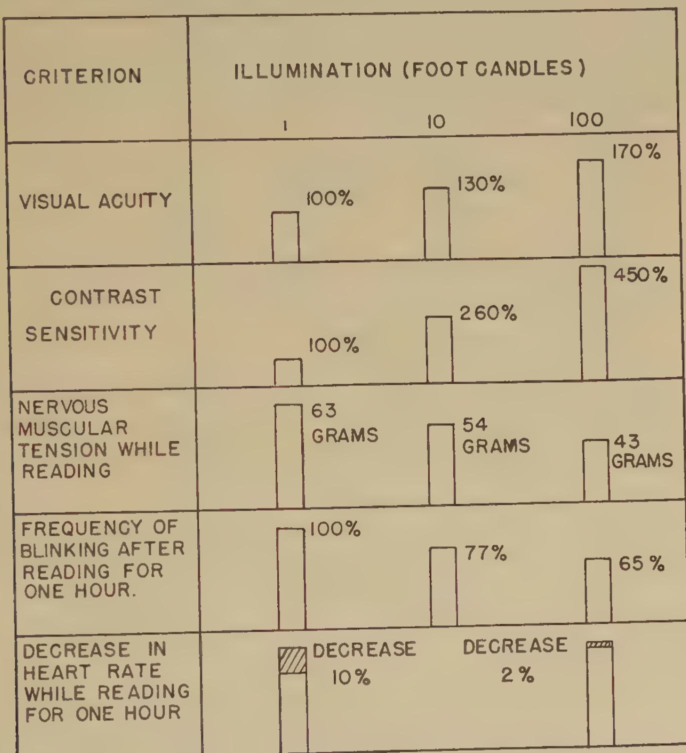

FIGURE 3. Effect of illumination intensity on visual functions.

terms and their relations, but also the fundamental concept of the effect of brightness on seeing. Slauer,[11] Luckiesh,[9] and numerous other engineers[12] and physiologists have done pioneer work in this field and have clarified some of the confusing issues. In the last few years, when the recommended minimum values of illumination intensity were considerably increased, the problems of brightness became more important than ever before. At present, we are talking frequently about brightness engineering, thus emphasizing the importance of brightness in illumination engineering.

Numerous tests carried out in recent years have shown that many of the seeing criteria are changing considerably with the illumination intensity.[9] FIGURE 3 shows some of the effects of an increased illumination

level on various visual tasks. In FIGURE 3, the effect of 1, 10, and 100 foot-candle illumination is shown on visual acuity and on contrast sensitivity. Both seeing criteria increase with the illumination intensity up to a certain maximum. Visual acuity is a basic factor not only in reading but for most of the work we have to perform. The importance of contrast sensitivity was shown in the experiments described above. (The effects of illumination intensity upon contrast sensitivity are shown in FIGURE 3 for a specific case, in which the size of the object is 1.8 minutes and the brightness contrast 7:32.) Muscular tension in reading decreases rapidly with increasing illumination intensity. FIGURE 3 further shows the frequency of blinking after reading for one hour at different illumination levels. It is an established fact that the frequency of blinking decreases with the increase of illumination intensity. Tests concerning the heart rate as a function of illumination intensity while reading showed that the decrease in heart rate

BRIGHTNESS OF SURROUNDING	RATE OF BLINKING
5X THAT OF TASK	110
SAME AS TASK	100
1/5X THAT OF TASK	108
1/25 X THAT OF TASK	117
1/100X THAT OF TASK	124

FIGURE 4. Rate of (involuntary) blinking while reading.

during one hour of reading is higher at a low illumination level than at a higher illumination intensity.

In order to avoid any misunderstandings concerning the blink rate, we quote from a letter recently received from Dr. Luckiesh, who has done most of the experimental work on blink rate as a function of illumination: "For a decade preceding the war we prosecuted 42 separate investigations dealing with the blink rate. In our hands this proved to be a sensitive criterion. I would not say that it is a criterion of fatigue, but rather an indication of tenseness or strain."

The rate of blinking is greatly affected by the brightness contrast, which is the ratio brightness of task/brightness of surrounding. FIGURE 4 shows that the rate of blinking is at a minimum when the brightness of the surrounding is the same as that of the task, and that it increases when the brightness contrast is above or below this ratio.

It is an established fact that higher intensities of illumination enable visual tasks to be performed with higher precision and greater speed. Tests

have shown that higher levels of illumination are also capable of reducing the internal (psycho-physiological) human energy losses, and the diagram in FIGURE 5 may be regarded as a composite representing the numerous researches of the last few years.

According to these researches, there is no doubt that human efficiency is greatly affected by light and illumination, whether we refer to human individuals or to the total of individuals in an industrial plant: the efficiency of a plant is based on the efficiency of its members.

What illumination can do in an industrial plant is shown in FIGURE 6. The above-mentioned data enable us to understand the great effect of light and light distribution on the accuracy and the speed of vision and, therefore, on the accuracy and speed of the total work performed. Good illumination not only brightens the object, but also the surroundings, and makes seeing

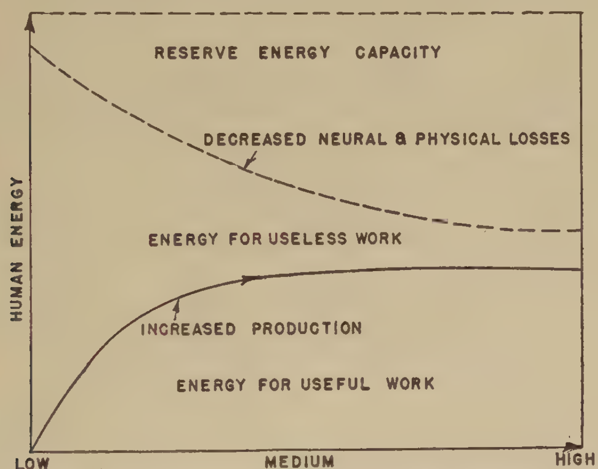

FIGURE 5. Expenditure of energy in the performance of a seeing task as a function of low, medium, and high illumination level.

easier. Accuracy and speed of vision, brightness of surroundings, and the seeing conditions in a general way determine, to a great extent, the number of accidents within a plant. It is needless to emphasize that the reduction of accidents increases the plant efficiency.

Increase in the accuracy and speed of vision may cause an increase in the plant production. It increases the quality of the products and reduces spoilage. In other words, it makes the plant operation more economical. Bright surroundings and easy seeing conditions may increase order and cleanliness, lessen the eye fatigue, and prevent eye strain. These facts improve the morale and make supervision easier. The interaction between the human being and the machine he operates, the psycho-physical system, as we call it, is a function of light and illumination.

The progress in illumination engineering is due to the efforts made by scientists and engineers. Illumination engineering is in the state of becoming a science. P. Moon, of the Massachusetts Institute of Technology,

introduced the mathematical methods for solving problems of illumination. His mathematical analysis not only enables us to understand the problems better, but also to improve seeing conditions. S. Hecht, the great biophysicist of Columbia University, who died recently, studied, analyzed, and explained the chemical reactions within the rods and cones of the retina of the human eye as a function of the intransigent light radiation.[4] It was Hecht who discovered the correlation between the process of seeing and the vitamin A.[5] Mention must be made of the pioneer in illumination, Matthew Luckiesh, the great scientist and engineer to whom we are indebted for most of the progress in understanding the effect of light radiation on human efficiency, welfare, and comfort.[9]

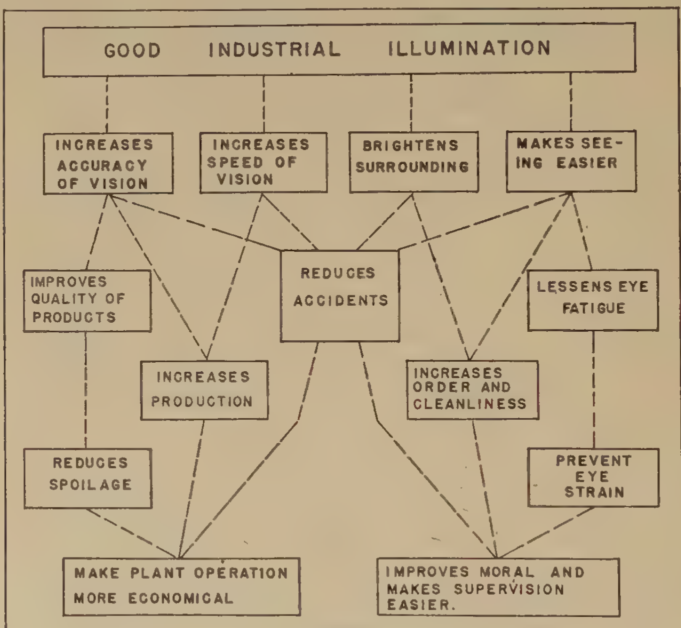

FIGURE 6.

Dr. Luckiesh developed such new instruments as the brightness meter, which enables us to determine brightness directly in foot-lamberts without any assumptions and calculations, and the visibility meter, a device to test threshold visibility. The latter device consists of two identical circular gradients which are rotated before the eyes to alter the brightness contrast of the objects, the visibility of which is to be measured.

As far as I know, it was Luckiesh who determined the specific characteristics of the process of reading and similar visual processes from his records of the eye movements of subjects possessing normal vision and skill in reading.[10] His data were obtained by means of an oscillograph, recording the changes in electrical potential between electrodes placed at the center of the forehead and at the right temple respectively, while the eyes performed

reading and swept along one line of print after another. The low potentials required enormous amplification in order to obtain records similar to the one shown in the myogram (FIGURE 7). The respective tests were made at illumination levels of 1 and 100 foot-candles for more than one hour. The myograms do not allow conclusions on the fatigue of the test persons, but they show that the time of reading one line decreases considerably with an increase in illumination. The time required to read a line of print increased 18 per cent during one hour of reading under 1 foot-candle, while it increased only 4 per cent when the reading was performed under 100 foot-candles. There is hardly any doubt that the myogram is a valuable tool in analyzing the muscular process while seeing.

Investigations of electrical potentials in the extrinsic muscles of the eye are said to be showing progress under Dr. M. E. Bitterman of Cornell University, and a program along similar lines is being started at M.I.T.

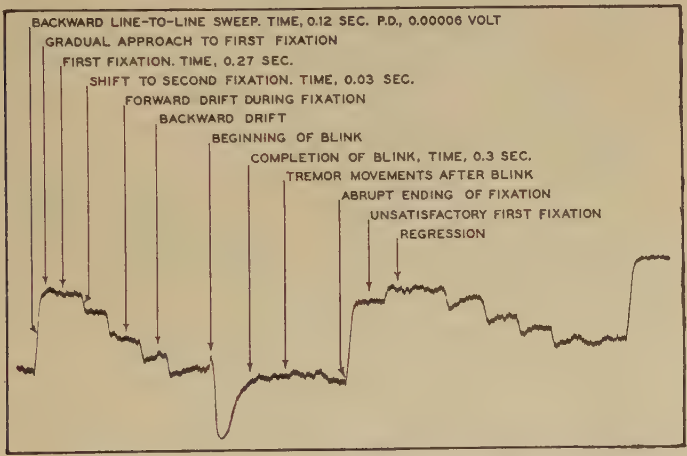

FIGURE 7. An electromyogram made while a typical educated adult subject read two consecutive lines of print.

under the sponsorship of the Illumination Engineering Society Research Fund.[1]

The advancement of science and engineering technique during the last few years brought us in contact with an increasing amount of complicated seeing tasks. I am referring, especially, to that part of human engineering which is concerned with the work on instrument panels such as are found in airplanes, ships, *etc.* Frequently, the operator of these instruments receives light signals under a certain angle with his actual seeing direction. I am talking about those light signals which are received at the periphery of the visual field. Experiments made by Russian scientists and published in the U.S.A. have shown that the limits of the visual field for different colors could be influenced by acoustic stimuli such as sound or noise. Yakolev[14] and Kravkow found that acoustic excitations may influence the limits of the visual fields for color stimuli such as are shown in FIGURE 8. They showed that the limits of the visual fields for blue and green colors expand under the

influence of acoustic stimuli and that they contract for the red-orange. We were informed also that no changes at all exist for the extreme long-wave

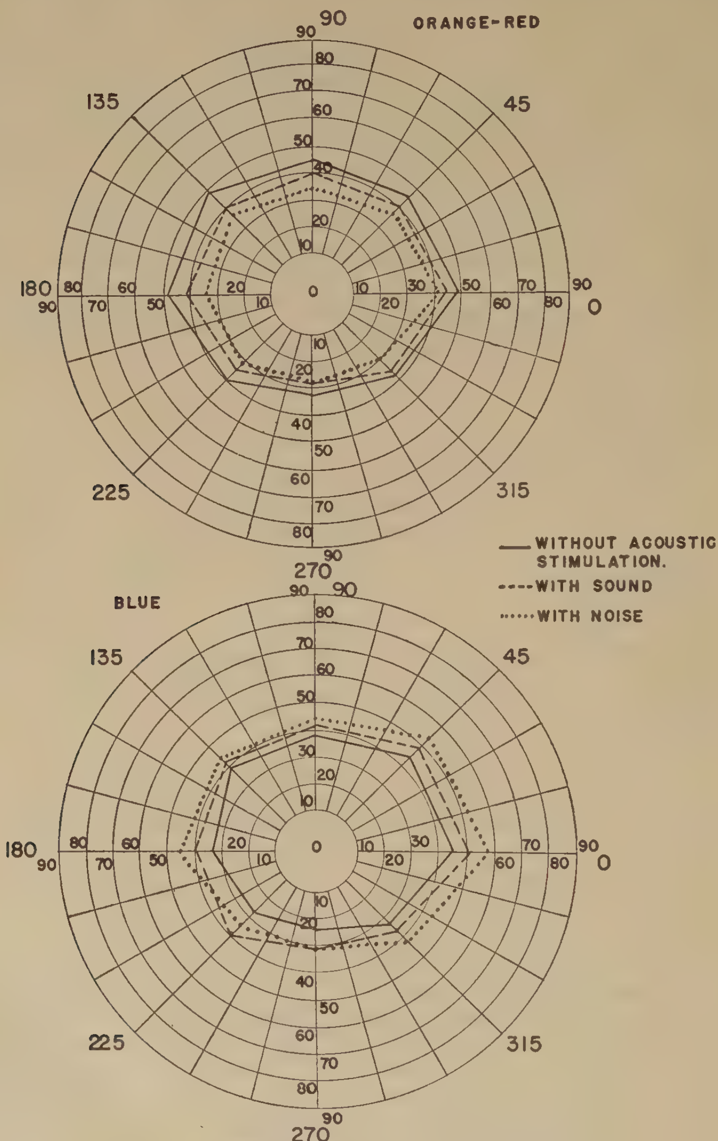

Figure 8. Limits of the visual field.

red. These physiological facts may be of greatest importance for the operator of airplane instrument panels.

There are also certain possibilities to increase some visual criteria, such as the eye sensitivity, by physical means. Kravkow and Galochkina,[8] of

the Ophthalmological Institute in Moscow, USSR, showed that a weak electric current running through the eye ball may noticeably alter the sen-

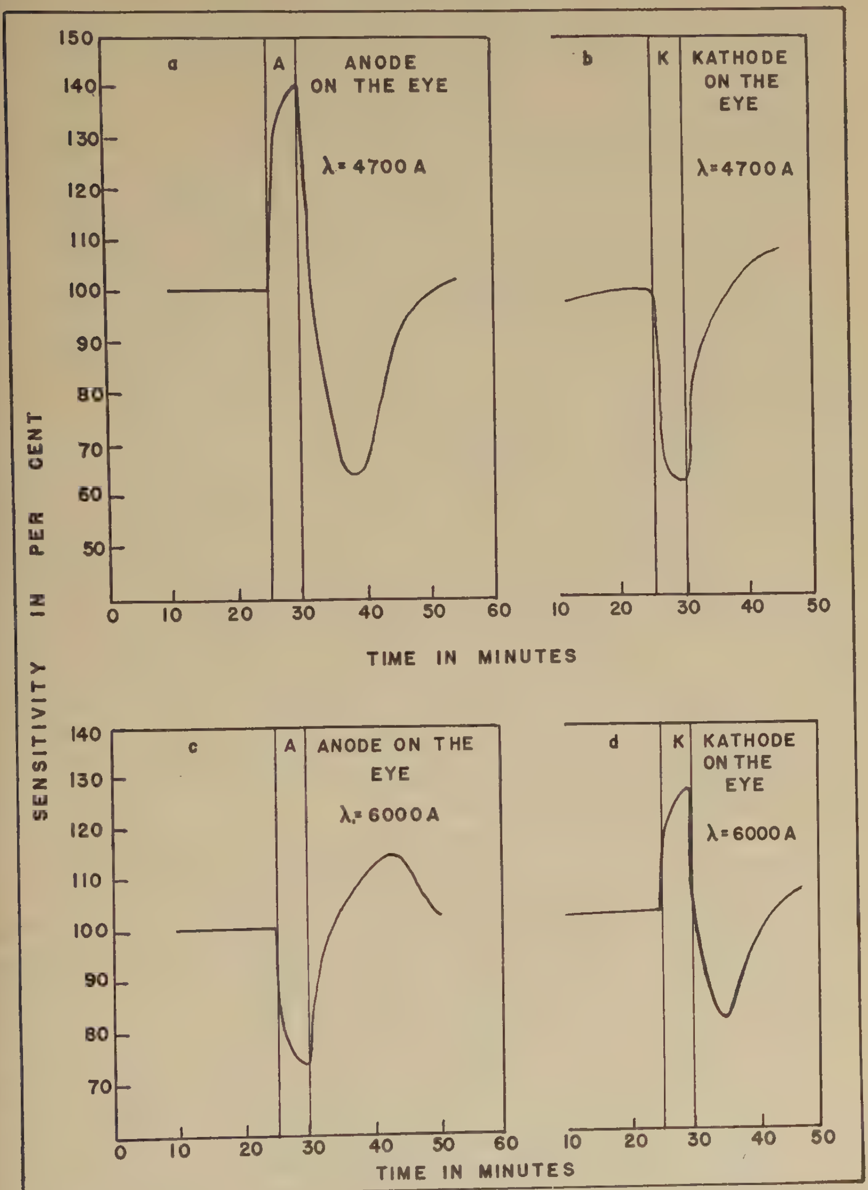

FIGURE 9. Effect of a constant electric current passing through the eye on the cone sensitivity for 4,700 and 6,000 radiation.

sitivity of rod vision as well as that of cone vision. In FIGURE 9, it is shown that the direction of these changes of sensitivity depends upon which of the

poles is placed on the eye ball. In the case of cone vision, such as shown in FIGURE 9, the tests were made with a current intensity of 0.02 m.a. The direction of these changes is influenced by the wavelength of the light stimulus. Both the increase and the decrease in sensitivity are quite remarkable. It has not been decided, as yet, whether these experiments will find practical application.

Although this report is by no means complete and gives only a few examples of the effect of light and illumination on the visual efficiency, and, therefore, the human efficiency, I do not wish to omit a brief review of one of the most interesting researches in the field of illumination engineering, that done by Dr. D. B. Harmon[2] on the effect of lighting and child development. Dr. Harmon is the director of one of the divisions of the Department of Health in the state of Texas and an Executive Director of the Texas Inter-Professional Commission on Child Development. Dr. Harmon's position in the state of Texas allowed him to study the health conditions of 160,000 elementary school-children in over 4,000 classrooms and to conduct a careful research into the effect of illumination on health and mental growth of a selected group of these children.

The primary task of a child, in Dr. Harmon's opinion, is to grow—to increase in dimensions and proportions toward his inherent adult size. The process of growing up is beset by many hazards, the general direction of which is determined by structural materials laid down by each child's heredity. The ultimate health and efficiency of each individual is determined by how well the laws of mechanics, chemistry, physics, biology, and psychology are utilized in arranging environments for the growing child. The illumination engineer has at least two concerns in determining these eventual efficiencies: a psychological one, and one in the field of the physiology of growth. We showed some of the psychological factors at the beginning of this paper. Each child may be considered a total unit which cannot be separated into physical, mental, economic, and social entities—a totality which is constantly undergoing alterations to maintain an integration of parts which are in various stages of completeness in their own growth and development. Any distortion of any of these parts distorts or limits the growth and development of the whole. Theoretically, poor lighting, for example, might not only be damaging to a child's vision and posture but eventually might also affect adversely his nutritional status because of excessive energy demands, and, consequently, increase his susceptibility to infection. Dr. Harmon showed that this theoretical statement can be proven by facts.

In his Texas program, Dr. Harmon made measurements of the relations of the head, body, and eyes to working area, and of the actions of various nerve connections and muscles of the body used in such performance, on several thousand children engaged in close visual-centered activities such as reading, writing, and drawing, when those children were working under adequate lighting and free of the restraints of badly proportioned desks and seats.

In November, 1942, Dr. Harmon undertook a lighting experiment with 396 children enrolled in the five grades of an urban school. The children were given thorough medical and nutritional examinations and visual,

psychological, educational, and other tests. The results of these examinations and tests are shown in FIGURE 10. Of these children, 53.3 per cent had refractive eye problems in a degree sufficient to interfere with the successful performance of their school work; 39.5 per cent of them had non-refractive eye problems—postural distortions interfering with successful binocular approach to close visual work and ocularly related nutritional deficiencies; 71.3 per cent had nutritional problems; and 75.2 per cent showed signs of chronic infections as reflected by ear, nose, and throat signs.

	% CASES TESTED		%		% REDUCTION IN NOVEMBER CASES.	% CHANGES IN TOTAL CASES.
	NOV. 1942	MAY 1943	CASES SHOWING ON BOTH EXAMS.	NEW CASES ON MAY EXAMS.		
CHILDREN WITH REFRACTORY EYE PROBLEMS.	53.3	22.8	18.6	4.2	−65.0	−57.1
CHILDREN WITH NON-REFRACTORY EYE PROBLEMS.	39.5	3.8	3.1	0.7	−92.1	−90.1
CHILDREN WITH NUTRITION PROBLEMS	71.3	39.5	37.2	2.3	−47.8	−44.5
CHILDREN WITH EAR, NASAL, & THROAT PROBLEMS *	75.2	51.2	42.6	8.6	−43.3	−30.9

FIGURE 10. Results on the medical examination of 396 children by Dr. Harmon before and 6 months after improvement of light in classrooms. (* = used as an examination index of chronic infections.)

ACHIEVMENT OF GROWTH BY MONTHS OF EDUCATIONAL AGE FROM NOV. 1942 TO MAY 1943. (6 MONTHS)	RANGE OF GROWTH	MEAN CHANGE	% CHANGING	
			6 MONTHS OR LESS	MORE THAN 6 MONTHS
EXPERIMENTAL SCHOOL WITH IMPROVED LIGHTING CONDITIONS.	0 TO +32	+10.2	+24.0	+76.0
CONTROL SCHOOL	8 TO +18	+6.8	+66.6	+33.3

FIGURE 11. Educational growth of 396 children as determined by Dr. Harmon after a 6 months period of improved light conditions in classrooms.

Immediately following the examinations and tests of these children, the 21 classrooms were rearranged to reduce sky glare as much as possible and redecorated to secure better distribution of natural light. Children who had been previously exposed to sky glare were rotated away from the windows 50 degrees. This rotation was sufficient to exclude affective sky glare from their eyes and yet was not so great as to bring their bodies into the line of light to their work. Back wall blackboards were eliminated. The remainder of the blackboards were covered with a light-color material.

Photometric measurements made when the children were in each room showed that on a clear mid-morning in November these decoration changes raised the horizontal illumination intensity to a great extent; previous 5 foot-candles at the inner wall were increased to 19 foot-candles. In addition, every child had a working surface free of body- and other shadows and a visual field free of glare. In May, 1943, six months after the rooms had been redecorated, the children were again given the same careful examinations as in November, 1942. More than 50 per cent of the children with refractory eye problems had improved considerably. Only 3.8 per cent had nonrefractive eye problems—a 90.1 per cent reduction in these problems from those recorded in November. The nutrition problems had dropped to 39.5 per cent of the children, and the signs of chronic infection had been reduced 30.9 per cent below the record of six months ago.

In addition to the apparent improvements in physical well-being resulting from better use of natural light, some comparable results were obtained in educational achievement as well (FIGURE 11). An objective achievement test, measuring educational growth in terms of months of educational age, was given the children at the beginning and end of the six months' period. The same test was given to a comparable group of children in a comparable control building in which no lighting changes or room rearrangements were made. FIGURE 11 shows that the children in the experimental school grew a mean average of 10.2 per cent in educational age, whereas, in the control school, the mean educational growth was 6.8 per cent.

Having reached this point in drafting the manuscript and searching for a concluding sentence, I could not find any words better than those which Dr. Harmon used at the end of his report on child development: "Lighting has a considerable influence on the growth and development and health of our children. In fact, with all the data before me, I would not hesitate to say that the illuminating engineer has a very important part to play in promoting the efficiency, the productivity and the well-being of tomorrow's people."

Bibliography

ALLPHIN, W. 1948. The search for a criterion of good seeing. The Sylvania Technologist **1**(2).

HARMON, D. B. 1945. Lighting and child development. Ill. Eng. **40**(4): 199–233.

HARRISON, W. 1945. Glare ratings. Ill. Eng. **40**(8): 525–540.

HECHT, S. 1937. Rods, cones, and the chemical basis of vision. Phys. Rev. **17**: 239–290.

HECHT, S. & J. MANDELBAUM 1939. Relation between vitamin A and dark adaptation. J.A.M.A. **112**: 1910–1916.

JAHN, T. L. 1946. Brightness discrimination and visual acuity as functions of intensity. J. Opt. Soc. Am. **36**(2): 83–85.

JAHN, T. L. 1946. The kinetics of visual dark adaptation. J. Opt. Soc. Am. **36**: 659–665.

KRAVKOV, S. V. & L. P. GALOCHKINA 1947. Effect of a constant current on vision. J. Opt. Soc. Am. **37**(3): 181–86.

LUCKIESH, M. 1944. Light, Vision, and Seeing. Van Nostrand. New York.

LUCKEISH, M. & F. K. MOSS 1935. The effect of visual effort upon heart rate. J. Gen. Psychol. **13**: 131.

SLAUER, R. G. 1945. The confusion in brightness thinking. Ill. Eng. **40**(2): 89–105.

TAYLOR, A. H. 1942. Brightness and brightness matters. Ill. Eng. **37**: 19.

TINKER, M. A. 1946. Illumination standards. Am. J. Pub. Health. **36**: 963–73.

YAKOVLEV, P. A. 1938. The influence of acoustic stimuli upon the limits of visual fields for different colors. J. Opt. Soc. Am. **28**: 286.

THEORY AND METHODS FOR ANALYZING ERRORS IN MAN-MACHINE SYSTEMS

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Systems Research is a broad research program covering a great variety of fundamental and applied studies on naval information systems. Two important objectives of this program are: (a) the evaluation of naval radar equipment in terms of the accuracy, kind, and amount of information an operator can extract from it, and (b) the development of suitable techniques for carrying out these evaluations. The results of our efforts to accomplish the second objective form the substance of this paper.

The theory and methods to be discussed here are the result of cooperative speculation on the part of several individuals who have wrestled with these problems.† We can claim no genuine originality for these methods, however, since the equations and formulae upon which they depend have been available in statistical and mathematical literature for a long time. And yet, the practical researcher cannot find this material discussed in any single source except in the most abstract terms. The chief contribution of this paper, perhaps, is that (a) it develops systematically several important concepts and formulae for analyzing errors in complex man-machine systems, and (b) it demonstrates by practical examples the applications of these equations to the analysis of errors in such systems.

Our primary interest in these methods has been directed toward the solution of radar problems, but it has become increasingly apparent that the concepts involved apply equally well to many other kinds of intricate systems, such as are found in modern industry. Although we have had no occasion to observe these techniques at first hand in industrial situations, examples of their use can be found. Several industrial examples have been used in this paper to show the generality of the methods and possibly to suggest still further applications.

The Radar Problem

At first glance, radar problems might appear to be extremely specialized and of limited interest. It turns out, however, that their diversity actually provides the engineering psychologist with unusual opportunities for basic or applied research. For one thing, the enormous complexity of radar systems challenges the ingenuity of the investigator in this field. This complexity is due in part to the fact that radar systems deal with a rather nebulous product—information. Aboard naval vessels, for example, such a system is expected to provide up-to-date, accurate information on the location, range, altitude, speed, course, number, and identity of all aircraft

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within a large area. If there are 100 aircraft around a ship, this turns out to be a lot of information.

Radar problems are also complex because they involve such exceedingly intricate organizations of men and machinery—each a potential source of error and time delay. Consider, for example, how a ship directs its fire at night. Targets are detected by a search radar. The radar operator determines the bearing and range of each target and relays this information to another man who charts it on a plot-board. A fire-director officer, in turn, evaluates the plotted information and selects one or more targets to be fired upon. His decision is transmitted to another operator who picks up the target on another radar from which the guns are finally aimed. No further sophisticated analysis is necessary for us to recognize immediately that each link in this chain is a fallible one.

Even when a small part of the system is isolated for study, the problem is still complex. The ideal method for measuring the accuracy of a single radar and its operator would make use of a series of targets whose distances from the radar are very accurately known. To sample the radar's capacity adequately, and to avoid the possibility that an operator will memorize the locations of the targets, there should be a large number of these targets, *i.e.*, 50 or more. The targets should be distributed in all directions from the radar location, they should be located at distances of two to 100 miles, and their distances should be known to within a few yards. But the expense of setting up such an ideal testing range is so clearly prohibitive that substitute methods must be sought.

In lieu of a testing range, the ranges reported from one radar might be compared against the range reports from another radar. But any radar which is used as a standard has its own error, usually of unknown magnitude. Discrepancies will occur between the two radars—that we may be sure of. The real problem is: how much of the error can be assigned to the test radar and how much to the one being used as a standard?

Still another method might make use of an electronic device for producing artificial targets. The output of such a device can be fed into the radar to produce targets which appear quite realistic. But the problem is still not solved, because the target generating system has its own peculiar errors which interact with the errors in the radar circuits.

The whole problem, then, boils down to this: how is it possible to assess the accuracy of the information a man extracts from a radar when we know that (a) the radar is subject to error, (b) the man contributes some of his own error, and (c) the standard (either another radar or a target simulator) against which we compare the radar and operator has its own error? We must remember, too, that none of the three errors can be measured independently of the others.

The problem has a rough parallel in the field of precision instrumentation. Thus, in speaking about thermometers, Behar[2] states: "Since there is no such thing as absolute accuracy in the instrumental measurement of magnitudes such as temperature, and since the function of a measuring instrument is to assign to a measured magnitude a numerical value, *i.e.*,

a mathematically-usable quantity, it follows that 'accuracy' is the relation between the true value (of the magnitude) and the obtained value (of the quantity). The true value, of course, is a quantity obtained by means of a 'more accurate' instrument which has been certified by means of 'still more accurate' instruments defining the International Temperature Scale."

Kinds of Errors

Constant vs. *Variable Errors*. Because the word "error" is often used so loosely, it is necessary for us to examine closely the kinds of errors systems may exhibit. In their research, psychologists have frequently made a distinction between (a) constant errors and (b) variable errors. A constant error is the difference between the average of a large series of measure-

FIGURE 1. Target patterns of ten shots fired by two riflemen. A's pattern exhibits no constant error, but has rather large variable errors. B's pattern exhibits a large constant error, but small variable errors.

ments and the true, or expected, value. Variable errors are measured by some statistical quantity which defines the dispersion, or spread, of the individual measurements.

This distinction between constant and variable errors can be illustrated by a fairly simple example. In contests between expert riflemen, it is common practice for each rifleman to shoot a series of practice rounds. Shown in FIGURE 1 are the patterns shot by two riflemen, *A* and *B*. In general, rifleman *A* placed his shots around the central area. We would say that he exhibited no constant error. Rifleman *B*, on the other hand, has a rather large constant error. The average position of his ten shots is far from the center.

The variable errors for these two riflemen are shown by the spread of the individual shots on the target. Rifleman *A*, for example, is an inconsistent shooter. Although his sights appear to be accurately aligned on the target, he shows a great deal of unsteadiness. We would say that he exhibits large variable errors. Rifleman *B*, on the other hand, is an ex-

tremely consistent shooter. His variable errors are very small even though he has a large constant error.

This distinction between the two kinds of errors has also been made in the field of accurate instrumentation. Thus, Behar[2] states: ". . .Intrinsic accuracy implies other measuring properties, because its determination involves a more or less complete calibration, in the course of which it may be found that the error varies not only for different true values but for the same true value when successive measurements are made."

Another writer in this field, Schlink,[8] states: "The third important factor to determine in the calibration of a measuring instrument is that of variance, which is defined as the range, at any given value of the measured quantity, of variation in reading which may be exhibited by the instrument under repeated application of the same value of the quantity being measured, after a steady reading has been attained, the environment remaining unchanged. This quantity. . .may also be called the range of uncertainty of indication, in that it represents the range within which the readings may be expected to lie when all causes of variation save those inherent in the instrument are eliminated."

The radar problem turns out to be very similar to the shooting problem despite the enormous increase in the complexity of the machinery involved. A radar operator takes a sight, as it were, on a distant target. He reports a range for the target. The difference between his reported range and the true range of the target constitutes an error. Let us designate the range reported by the radar operator as R_R. Let us also designate the true range of the target as R_T. The error, ϵ, is $R_R - R_T$. The subtraction is always carried out in this order. This means that an error may be minus, *i.e.*, the radar range is short of the true range, or plus, *i.e.*, the radar range is greater than the true range.

When we obtain a large number of such error measurements in our work, we usually find symmetrically distributed sets of values, as shown in FIGURE 2. The mean error—the constant error—is determined by computing the average of all these measurements. The statistical measure most commonly used for this purpose is the arithmetic mean. Its formula is familiar as the sum of the individual errors divided by the number of them:

$$M_\epsilon = \frac{\Sigma\epsilon}{N}. \qquad (1)$$

Note, however, that, in computing the sum of the errors, $\Sigma\epsilon$, the sign of each error must be taken into account. The average error for the set of data in FIGURE 2 turns out to be +138.8 yards. This means that, on the average, this radar operator using this radar tended to read the range as 138.8 yards too great.

But it is also evident from FIGURE 2 that there is a lot of dispersion in the errors obtained. There were several instances, for example, in which the radar operator reported the range of the target to be 1,000 yards greater than the true range. There were also a few instances in which the radar operator underestimated the true range of the target by 1,000 yards. This

spread of errors—these inconsistencies—are what we mean by variable errors.

In engineering work, it is customary to use the maximum limits of the errors obtained as a measure of the variable errors of the instrument. In the quotation from Schlink[8] cited above, for example, the variance of a measuring instrument is defined as the range* of variation in readings which results when the same quantity is measured repeatedly. The range of

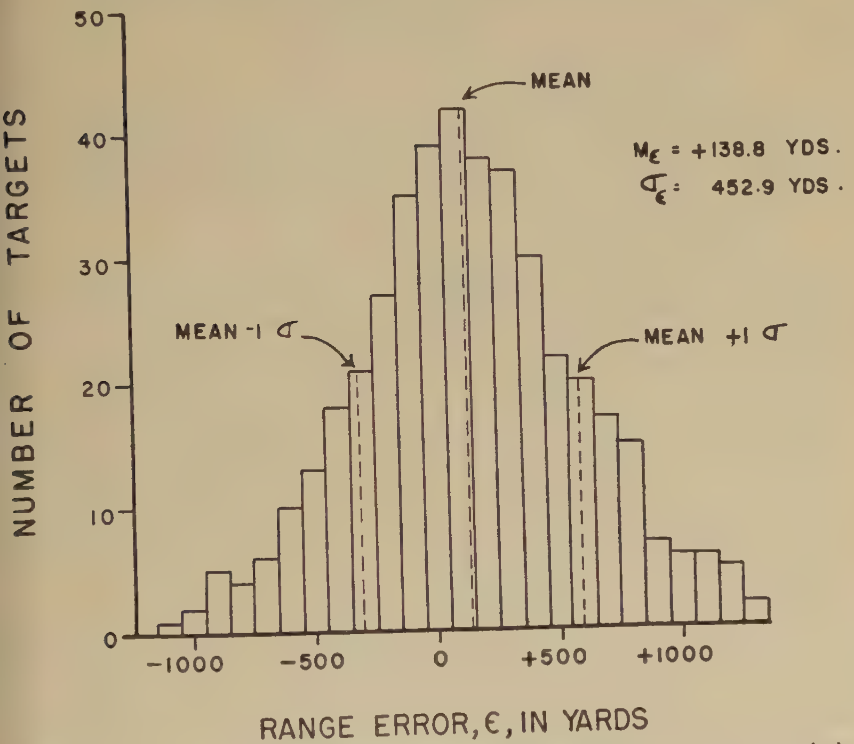


FIGURE 2. Histogram of 428 errors in range obtained with a modern radar. Each measurement is the difference between the range reported by the radar operator and the true range of the target.

errors for the radar data shown in FIGURE 2 is the difference between the highest and lowest errors found, *i.e.*, 2,400 yards.

Although the range of errors is a convenient quantity to compute, it is not a satisfactory measure of the variable errors in a system. In the first place, the range, or variance in Schlink's terminology, depends on only two measures—the highest and lowest. For this reason, statisticians have been able to show that it varies greatly from one series of measurements to another.[5, 11] In addition, the range of errors usually increases as the number of observations increases. This is the case because the probability of finding extremely deviant errors increases with a greater number of

* The word "range" in this connotation refers to a statistical quantity.

observations. A second objection, and a more serious one for our purposes, is that the range of errors cannot be used in equations which involve algebraic manipulation. As we shall see, such equations are essential to the analysis of component errors in man-machine systems.

For these reasons, statisticians usually prefer to use the standard deviation—symbolized by the small Greek letter σ, called "sigma"—as a measure of variable errors. The standard deviation is the root-mean-square of the deviations from the mean of the distribution. Its formula is:

$$\sigma_\epsilon = \left[\frac{\Sigma(\epsilon - M_\epsilon)^2}{N}\right]^{1/2}. \tag{2}$$

The standard deviation makes use of every measurement which was obtained, and is considerably more stable than the range of values. As we shall see later, the standard deviation has some other very valuable properties for our purposes. For the data of FIGURE 2, the standard deviation of the errors is 452.9 yards.

The standard deviation is a measure of the dispersion of measurements around the average value. The larger the standard deviation, the more widely dispersed are the measurements. The smaller the standard deviation, the more closely do the measurements fall around the mean value. This state of affairs is summarized pictorially in FIGURE 3, which shows two distributions of range errors obtained from two different radars. Both have the same average error, *i.e.*, the same constant error. But we can see that one radar has small variable errors, *i.e.*, in general, the errors are very close to the mean value. The other has much larger variable errors, *i.e.*, the measurements tend to be widely dispersed around the average value. Another way of saying this is that one radar is more consistent than the other.

When measurements are normally distributed,* the average and the standard deviation of the measurements enable the statistician to make some fairly precise statements about the distribution. For example, he can predict that 68.6 per cent of all the measurements will lie between the mean and $\pm 1\sigma$ (*cf.* FIGURE 2). He can also predict that about 95.4 per cent of the cases will lie between the mean and $\pm 2\sigma$. From tables of the normal curve, he can also predict what percentage of the total number of observations will lie between the mean and fractional parts of the standard deviation. For example, 50 per cent of the cases can be expected to fall between the mean and $\pm 0.6745\sigma$. These two statistics, then—the mean and the standard deviation—serve a very useful purpose in describing or summarizing large sets of measurements.

This analysis of radar errors has its analogy in industry. In quality control work,[9] the average value tells the statistician whether a process is centered satisfactorily. A constant error, in our terminology, means that control is at the wrong level. Control is at too high a level if the constant error is positive, *i.e.*, if the average is higher than that called for by the specifications. Control is at too low a level if the constant error is nega-

* Data are normally distributed when they have the general shape shown in FIGURE 3. Although it is beyond the scope of this paper to discuss this matter in greater detail, it is known that many physical, industrial, biological, and psychological data are normally distributed.

tive, *i.e.*, the average is lower than specified. Similarly, a manufacturing process is said to be controlled if the variations of the items around the average are small. This is another way of saying that the standard devia-

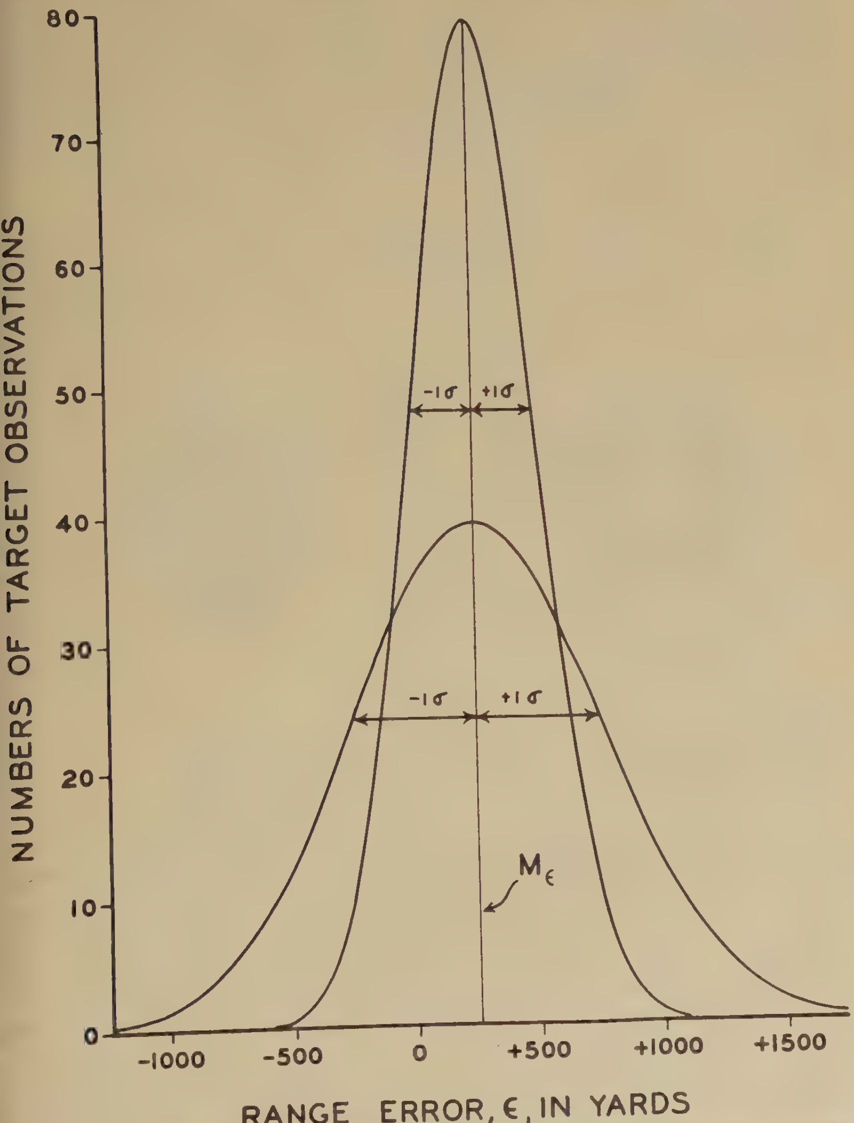


FIGURE 3. Distributions of 1,000 range errors obtained with two different radars. The standard deviation, σ, is directly related to the magnitude of the variable errors.

tion of the measurements is small. A controlled manufacturing process, therefore, produces items with a high degree of uniformity.

Distributions of variable errors in industrial applications are not seen

very often because inspection is usually on a go-no-go basis. But the variability is there nonetheless, and the industrial statistician can occasionally put these concepts to practical use in high production manufacturing. Alger,[1] for example, gives an example in which 15 per cent of frequency relays were being rejected because they fell outside the tolerances allowed in specifications. Plotting a distribution curve of the measurements showed that all of the rejections were on the high side. This means that the manufacturing process was centered at too high a level. A shift in the calibration settings of the machines, *i.e.*, changing the mean of the distribution, reduced the rejections to a trivial amount without any design or manu-

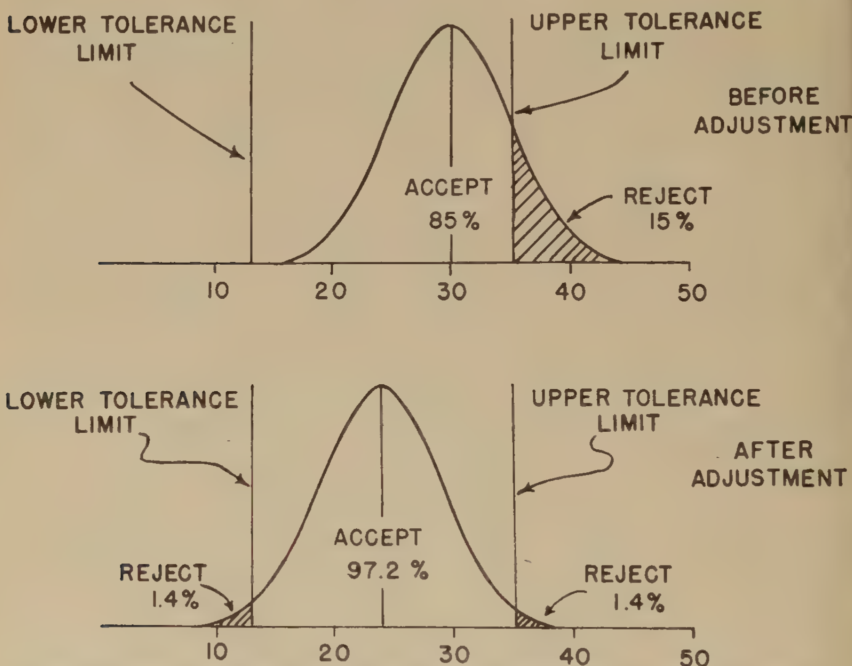


FIGURE 4. Showing how the percentage of rejects in a manufacturing process was reduced by shifting the calibration, *i.e.*, changing the constant error, without changing the variable errors.

facturing change. FIGURE 4 illustrates the situation schematically. Shifting the average, without changing the variability of the units, reduced the rejects from 15 per cent to only 2.8 per cent.

Constant and Variable Errors. For some purposes, it is convenient to have a measure of the constant and variable errors together. This, apparently, is what instrument makers mean by the limit of error. It is the maximum error obtained in calibrating an instrument when no differentiation is made between the constant and variable errors of the instrument. Thus, Behar[2] states: ". . . . the intrinsic accuracy of an instrument is the resultant of its measuring properties. It usually is expressed in terms of the *limit of error*, defined by the Scientific Apparatus Makers of America

as 'the maximum error by which the readings of an instrument will depart from true values.'"

Since the limit of error is dependent on only one value—the most deviant error in a series of measurements—and is subject to the objections raised above with regard to the range of variable errors, we shall define a new measure, ${}_0\sigma$, as the root-mean-square of the errors around the zero error, *i.e.*, around the true value. ${}_0\sigma$ is equal to the root of the second moment of a series of measurements. Its defining equation is:

$$ {}_0\sigma_\epsilon = [\mu_2']^{1/2} = \left[\frac{\Sigma\epsilon^2}{N}\right]^{1/2}. \qquad (3)$$

The Relative Importance of Constant and Variable Errors. Having defined constant and variable errors, we might ask: Which is the more im-

FIGURE 5. Same patterns of shots as illustrated in FIGURE 1. The constant error in rifleman B's pattern has been corrected by suitable adjustments in his sights. Notice that B now gets a perfect score. No adjustment in A's sights, however, will give him a perfect score.

portant? Let us return for a moment to the target patterns shot by the two riflemen (FIGURE 1). At first glance, you might say that *B* is a very inaccurate shooter. And yet any rifleman will tell you that this is not the case at all. *B* is a much better shooter than *A*. The reason is this: the large constant error in the trial shots fired by *B* can be compensated for very easily by simple adjustments in his sights. With suitable corrections in elevation and windage, rifleman *B* will turn in a perfect score (*cf.* FIGURE 5). In rifle shooting, then, constant errors are not the important ones, because they can be very easily adjusted for by changing the position of the sights on the gun. The really important errors are the variable errors. No correction of the sights on *A*'s gun will make all of his shots fall in the center bull. He is inherently much too variable.

As in the shooting example, constant errors in radar systems are less important than variable errors, since it is always possible to correct for them. It is the variable errors which are the true indicators of the inherent in-

stabi.ity or inaccuracy of a system. To illustrate: If operators on a radar always read ranges as 500 yards short of the true range, we could rectify the error by a simple correction in the electronic circuits or even in the dials. The real source of difficulty, however, lies in the fact that an operator will give a series of readings, the first of which is 500 yards too short, the next 400 yards too great, the next 1000 yards too short, and so on. The reduction of these annoying variable errors constitutes one major objective of Systems Research.

Corrections for constant errors are used even in the field of instrumentation. In the use of certain precision instruments, constant errors are rectified by correction data furnished with the instrument. The better grades of fever thermometers used in hospitals are a good example. Each thermometer has been laboratory tested against accurate standards and is accompanied by a chart (*cf.* TABLE 1) which shows the magnitude of the calibration or constant error. The variable errors for such an instrument are usually very small, indicating great inherent precision or stability. Thus, the thermometer which had the constant errors shown in TABLE 1

TABLE 1

CALIBRATION CHART SUPPLIED WITH A HIGH-GRADE FEVER THERMOMETER*

Reading	*Correction*
98°	−0.1
102°	+0.1
106°	+0.3

* This is a correction for constant errors. When the correction is +, it must be added to the observed reading, and when −, subtracted.

was certified to reproduce the same temperature within 0.1 degree on repeated trials.

This distinction between the relative importance of constant and variable errors is so essential to this discussion that we shall look at another example. Coakley[4] measured the weights of stockings which were made by machines adjusted to manufacture them in sizes 9.5, 10, and 10.5. The distributions he obtained are shown in FIGURE 6. On the average, the size 10.5 stockings were heavier than the size 10 and these, in turn, were heavier than the size 9.5 stockings. But it is not the average weight which is important here. By a simple adjustment in the machines, the operator can make stockings come out heavier or lighter as he pleases. He can adjust for any constant error, in short.

The real problem here arises from the variable errors. There was so much variability in weight that a customer buying size 9.5 stockings might actually get some which were heavier than some 10.5 in size. There was so much variability, in fact, that not even the heaviest size 10.5 stocking was heavier than *all* size 10's. Not only is the customer likely to be dissatisfied because of this variability, but it also makes the manufacturing process more difficult. If stockings vary a lot, it is much harder to match

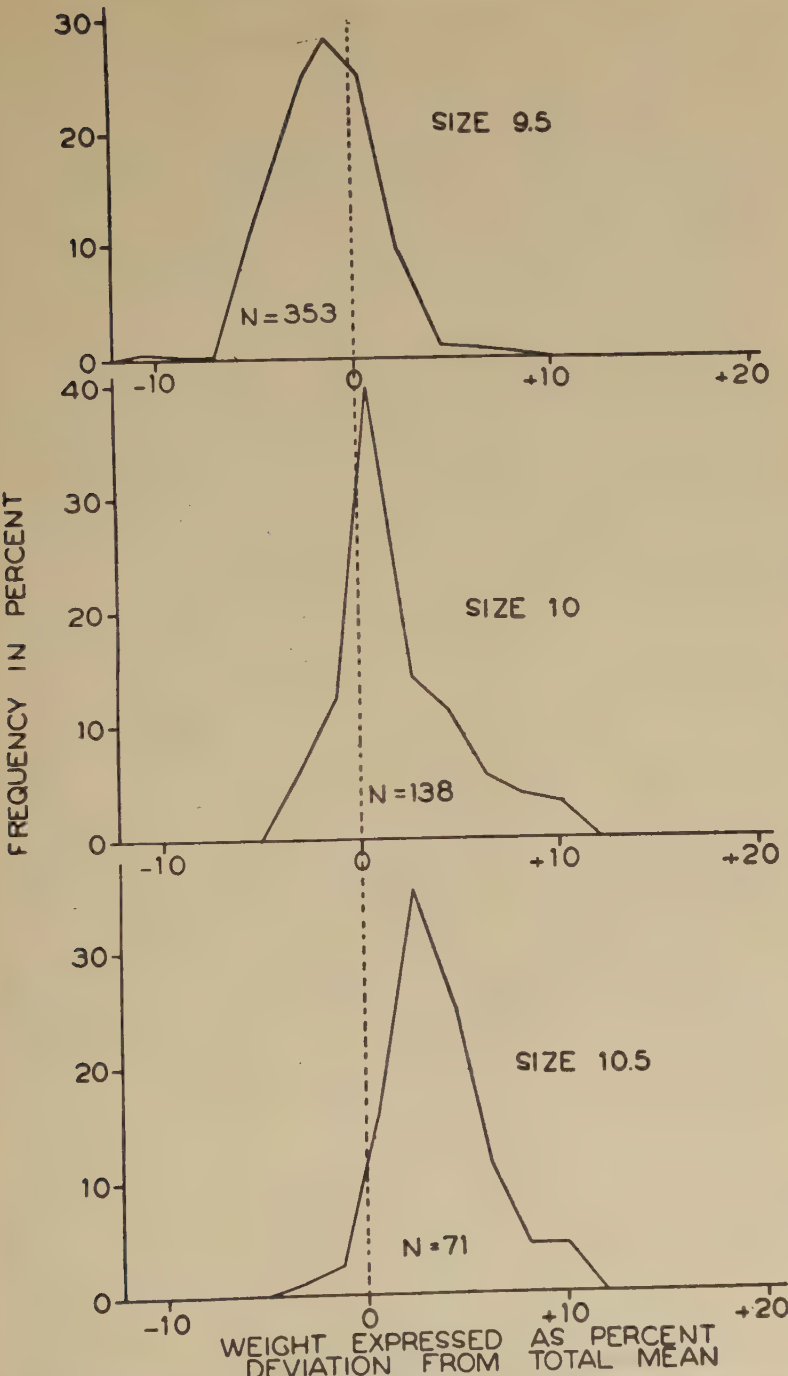


FIGURE 6. Distributions of weights of stockings made by automatic knitting machines adjusted to manufacture them in sizes 9.5, 10, and 10.5. (Data from Coakley.[4])

them up into pairs. So here, again, we see that it is the variable errors which indicate genuine instability in the man-machine relationship.

The Accumulation of Errors in Man-Machine Systems

There are usually many sources of error which contribute to variability in the final result. We have already had occasion to mention some of these in connection with radar. Some errors arise from the electronic circuits in the radar itself. The radar operator also contributes errors which are fairly large in most instances. We also know that both sources of errors occur in the use of precision measuring instruments. Some errors are due to the instruments themselves. A meter or gauge will not always come to rest at precisely the same point on repeated trials. Lag, friction, hysteresis, thermal expansion, and so on contribute to these instrument errors. But there are also some rather large human errors in the use of precision instruments. It is worth pointing out, incidentally, that the human error in using precision gauges, micrometers, and calipers is considerably greater than most supervisors or standards men expect. Lawshe and Tiffin,[7] for example, studied the accuracy and variability of measurements made by 200 inspectors and 45 experienced tool makers in using such instruments. Their data indicate a surprising amount of human error.

Even when the machine part of a system is completely automatic, or apparently so, the operator may still introduce some of his own peculiar errors into the quality of the final result or the finished product. In Coakley's study,[4] for example, the stockings were manufactured by automatic knitting machines operated by different workers. The operator's task was merely to pull certain levers at certain times. When he pulled these levers was determined automatically as the machine completed each stage of its task. It is difficult to see how an operator could add to, or subtract from, the number of stitches or the number of courses knit into a stocking. And yet when the same machine, using the same yarn, with the same adjustments, was run by different operators, the distributions of weights of stockings came out differently.

The engineering psychologist, who is faced with the problem of reducing variable errors in man-machine systems, must know how errors accumulate in a system in order that he may go about his task intell gently. The source of error which contributes most to the final variability is obviously the most economical one to tackle. This may seem to be so obvious that there is nothing more to say about it. But there is more to it than this, as we shall see.

Accumulation of Constant Errors. The rule for the accumulation of constant errors in a system is simple enough: they add algebraically. Suppose, for example, that a radar is miscalibrated so that on the average it reads 100 yards short of the true range, *i.e*, its constant error is -100 yards. Now let us suppose that we have a radar operator who, because of the way he aligns the range marker on a target, has a tendency to read 50 yards too high. On the average, and with a perfectly calibrated radar, he would give us range readings 50 yards too great. His constant error is $+50$ yards. Put the radar operator together with the miscalibrated

radar, and we will get range readings which are 50 yards too short, *i.e.*, $-100 + 50 = -50$.

The derivation of a formula showing how constant errors accumulate is simple. Let ϵ_X, ϵ_Y, ϵ_Z, $\cdots$, represent the errors contributed to the final measurement by components X, Y, Z, $\cdots$, of the system. In a radar system, for example, ϵ_X might be the error inherent in the electronics and mechanics of the radar; ϵ_Y might be the error attributable to the inherent inaccuracy of the radar operator; ϵ_Z might be the error arising when target information is plotted on a polar chart or map; and so on.

For any single target, the final or resultant error of the system, ϵ_T, is the sum of the component errors. Thus:

$$\epsilon_T = \epsilon_X + \epsilon_Y + \epsilon_Z + \cdots \tag{4}$$

Lest there be any misunderstanding about equation 4, let us assume some real numbers. A search radar picks up a target. Component X makes an error, ϵ_X, of, let us say, -10 yards. At the same time, and for the same target, component Y makes an error, ϵ_Y, of, let us say, $+20$ yards. Likewise, component Z contributes an error, ϵ_Z, of, let us say, -50 yards. The final error, ϵ_T, for this one target amounts to $-10 + 20 - 50$ or -40 yards. For the next target, components X, Y, and Z might contribute errors of, let us say, $+10$, -20, and $+30$ yards. The second target will thus be in error, ϵ_T, by $+20$ yards.

For N targets, the mean error is equal to:

$$M_{\epsilon_T} = \frac{\Sigma\epsilon_T}{N} = \frac{\Sigma(\epsilon_X + \epsilon_Y + \epsilon_Z + \cdots)}{N} \tag{5}$$

$$= \frac{\Sigma\epsilon_X}{N} + \frac{\Sigma\epsilon_Y}{N} + \frac{\Sigma\epsilon_Z}{N} + \cdots$$

$$M_{\epsilon_T} = M_{\epsilon_X} + M_{\epsilon_Y} + M_{\epsilon_Z} + \cdots \tag{6}$$

This last expression is the one desired. It states that the constant error in a total system is equal to the sum of the constant errors arising in individual components of the system.

Accumulation of Variable Errors. The derivation of an equation which shows how variable errors accumulate in a system is also straightforward. What we want is an expression for σ_{ϵ_T} where

$$\sigma_{\epsilon_T} = \sigma_{\epsilon_X + \epsilon_Y + \epsilon_Z + \cdots} \tag{7}$$

The derivation proceeds thus:

$$\sigma_{\epsilon_T} = \left[\frac{\Sigma(\epsilon_T - M_{\epsilon_T})^2}{N}\right]^{1/2} \tag{8}$$

$$\sigma^2_{\epsilon_T} = \frac{1}{N}\,\Sigma(\epsilon_T - M_{\epsilon_T})^2$$

$$= \frac{1}{N}\,\Sigma(\epsilon_T^2 - 2\epsilon_T M_{\epsilon_T} + M^2_{\epsilon_T}) \tag{9}$$

$$= \frac{1}{N}\,(\Sigma\epsilon_T^2 - 2M_{\epsilon_T}\Sigma\epsilon_T + NM^2_{\epsilon_T}).$$

But, by definition,

$$M_{\epsilon_T} = \frac{1}{N}\Sigma\epsilon_T. \tag{10}$$

Hence:

$$\begin{aligned} \sigma^2_{\epsilon_T} &= \frac{1}{N}\left[\Sigma\epsilon^2_T - 2\,\frac{\Sigma\epsilon_T}{N}\,\Sigma\epsilon_T + N\left(\frac{\Sigma\epsilon_T}{N}\right)^2\right] \\ &= \frac{1}{N}\left[\Sigma\epsilon^2_T - 2\,\frac{(\Sigma\epsilon_T)^2}{N} + \frac{(\Sigma\epsilon_T)^2}{N}\right] \\ &= \frac{1}{N}\left[\Sigma\epsilon^2_T - \frac{(\Sigma\epsilon_T)^2}{N}\right] \\ &= \frac{1}{N^2}\,[N\Sigma\epsilon^2_T - (\Sigma\epsilon_T)^2]. \end{aligned} \tag{11}$$

This last expression may now be written:

$$N^2\sigma^2{}_{\epsilon_T} = N\Sigma^2\epsilon_T - (\Sigma\epsilon_T)^2. \tag{12}$$

Into it, we must now insert $\epsilon_X + \epsilon_Y + \epsilon_Z + \cdots$ for ϵ_T. Thus:

$$\begin{aligned} N^2\sigma^2_{\epsilon_T} &= N\Sigma(\epsilon_X + \epsilon_Y + \epsilon_Z + \cdots)^2 - [\Sigma(\epsilon_X + \epsilon_Y + \epsilon_Z + \cdots)]^2 \\ &= N\Sigma(\epsilon_X + \epsilon_Y + \epsilon_Z + \cdots)^2 - (\Sigma\epsilon_X + \Sigma\epsilon_Y + \Sigma\epsilon_Z + \cdots)^2 \\ &= N\Sigma(\epsilon^2_X + \epsilon^2_Y + \epsilon^2_Z + \cdots + 2\epsilon_X\epsilon_Y + 2\epsilon_X\epsilon_Z + 2\epsilon_Y\epsilon_Z + \cdots) \\ &\quad - [(\Sigma\epsilon_X)^2 + (\Sigma\epsilon_Y)^2 + (\Sigma\epsilon_Z)^2 + \cdots + 2\Sigma\epsilon_X\Sigma\epsilon_Y \\ &\quad + 2\Sigma\epsilon_X\Sigma\epsilon_Z + 2\Sigma\epsilon_Y\Sigma\epsilon_Z + \cdots] \end{aligned} \tag{13}$$

$$\begin{aligned} N^2\sigma^2_{\epsilon_T} &= N\Sigma\epsilon^2_X + N\Sigma\epsilon^2_Y + N\Sigma\epsilon^2_Z + \cdots + 2N\Sigma\epsilon_X\epsilon_Y + 2N\Sigma\epsilon_X\epsilon_Z \\ &\quad + 2N\Sigma\epsilon_Y\epsilon_Z + \cdots - (\Sigma\epsilon_X)^2 - (\Sigma\epsilon_Y)^2 - (\Sigma\epsilon_Z)^2 - \cdots \\ &\quad - 2\Sigma\epsilon_X\Sigma\epsilon_Y - 2\Sigma\epsilon_X\Sigma\epsilon_Z - 2\Sigma\epsilon_Y\Sigma\epsilon_Z - \cdots \end{aligned} \tag{14}$$

The terms in equation 14 may be recombined as follows:

$$\begin{aligned} N^2\sigma^2_{\epsilon_T} &= [N\Sigma\epsilon^2_X - (\Sigma\epsilon_X)^2] + [N\Sigma\epsilon^2_Y - (\Sigma\epsilon_Y)^2] + [N\Sigma\epsilon^2_Z - (\Sigma\epsilon_Z)^2] \\ &\quad + \cdots + 2[N\Sigma\epsilon_X\epsilon_Y - \Sigma\epsilon_X\Sigma\epsilon_Y] + 2[N\Sigma\epsilon_X\epsilon_Z - \Sigma\epsilon_X\Sigma\epsilon_Z] \\ &\quad + 2[N\Sigma\epsilon_Y\epsilon_Z - \Sigma\epsilon_Y\Sigma\epsilon_Z] + \cdots \end{aligned} \tag{15}$$

The first three sets of terms are equal to $N^2\sigma^2_{\epsilon X}$, $N^2\sigma^2_{\epsilon Y}$, and $N^2\sigma^2_{\epsilon Z}$ by virtue of the identity established in equation 12.

Each compound term of the form, $2[N\Sigma\epsilon_X\epsilon_Y - \Sigma\epsilon_X\Sigma\epsilon_Y]$ is an integral part of the statistical formula for the coefficient of correlation between two variables. This formula is usually written:

$$r_{XY} = \frac{\Sigma(X - M_X)(Y - M_Y)}{N\sigma_X\sigma_Y}. \tag{16}$$

For our purposes, it is necessary to derive a variant of this basic formula. Thus:

$$\begin{aligned} Nr_{XY}\sigma_X\sigma_Y &= \Sigma(X - M_X)(Y - M_Y) \\ &= \Sigma(XY - XM_Y - YM_X + M_XM_Y) \\ &= \Sigma XY - M_Y\Sigma X - M_X\Sigma Y + NM_XM_Y. \end{aligned} \tag{17}$$

Noting again that $M_X = \frac{\Sigma X}{N}$ and that $M_Y = \frac{\Sigma Y}{N}$, we may write:

$$Nr_{XY}\sigma_X\sigma_Y = \Sigma XY - \frac{\Sigma Y}{N}\Sigma X - \frac{\Sigma X}{N}\Sigma Y + N\frac{\Sigma X}{N}\frac{\Sigma Y}{N}$$

$$= \Sigma XY - \frac{1}{N}\Sigma X\Sigma Y \tag{18}$$

$$= \frac{1}{N}(N\Sigma XY - \Sigma X\Sigma Y)$$

or

$$N^2 r_{XY}\sigma_X\sigma_Y = N\Sigma XY - \Sigma X\Sigma Y. \tag{19}$$

Note that the terms on the right of the equal sign in equation 19 are exactly parallel to the last three compound expressions in equation 15.

Having established this identity, we may now proceed with the primary derivation. The identities established in equations 12 and 19 can be inserted into equation 15 to give:

$$N^2\sigma^2_{\epsilon_T} = N^2\sigma^2_{\epsilon_X} + N^2\sigma^2_{\epsilon_Y} + N^2\sigma^2_{\epsilon_Z} + \cdots + 2N^2 r_{\epsilon_X\epsilon_Y}\sigma_{\epsilon_X}\sigma_{\epsilon_Y} + 2N^2 r_{\epsilon_X\epsilon_Z}\sigma_{\epsilon_X}\sigma_{\epsilon_Z} + 2N^2 r_{\epsilon_Y\epsilon_Z}\sigma_{\epsilon_Y}\sigma_{\epsilon_Z} + \cdots \tag{20}$$

$$\sigma_{\epsilon_T} = [\sigma^2_{\epsilon_X} + \sigma^2_{\epsilon_Y} + \sigma^2_{\epsilon_Z} + \cdots + 2r_{\epsilon_X\epsilon_Y}\sigma_{\epsilon_X}\sigma_{\epsilon_Y} + 2r_{\epsilon_X\epsilon_Z}\sigma_{\epsilon_X}\sigma_{\epsilon_Z} + 2r_{\epsilon_Y\epsilon_Z}\sigma_{\epsilon_Y}\sigma_{\epsilon_Z} + \cdots]^{\frac{1}{2}}. \tag{21}$$

Fortunately for us, there is no reason to suppose that the errors in one part of a radar system are correlated with the errors in another part of the system. Thus, it is entirely reasonable to expect that an error in the electronic circuits of a radar is independent of the error made by a radar operator. When it can be assumed that the errors contributed by components of a system are independent of each other, the r's in equation 21 equal zero and the whole expression reduces to:

$$\sigma_{\epsilon_T} = [\sigma^2_{\epsilon_X} + \sigma^2_{\epsilon_Y} + \sigma^2_{\epsilon_Z} + \cdots]^{\frac{1}{2}}. \tag{22}$$

In the derivation of equations 21 and 22, we have assumed that ϵ_T is the algebraic sum of component errors. Individual component errors may be plus or minus, but they are added algebraically to give ϵ_T. The reader can establish for himself that if we had defined ϵ_T as the *difference* of two errors, *i.e.*, $\epsilon_T = \epsilon_X - \epsilon_Y$, equation 22 would be unchanged. This means that if

$$\epsilon_T = \pm\epsilon_X \pm \epsilon_Y \pm \epsilon_Z \pm \cdots \tag{23}$$

equation 22 is still valid. Equation 21, however, is changed depending on whether component errors are added or subtracted. The following illustration is given without proof to show where the change occurs. If

$$\epsilon_T = \epsilon_X - \epsilon_Y - \epsilon_Z + \cdots \tag{24}$$

then

$$\sigma_{\epsilon_T} = [\sigma^2_{\epsilon_X} + \sigma^2_{\epsilon_Y} + \sigma^2_{\epsilon_Z} + \cdots - 2r_{\epsilon_X\epsilon_Y}\sigma_{\epsilon_X}\sigma_{\epsilon_Y} - 2r_{\epsilon_X\epsilon_Z}\sigma_{\epsilon_X}\sigma_{\epsilon_Z} + 2r_{\epsilon_Y\epsilon_Z}\sigma_{\epsilon_Y}\sigma_{\epsilon_Z} \pm \cdots]^{\frac{1}{2}}. \tag{25}$$

Equation 22 shows the magnitude of the variable error in a system as a function of the variable error contributed by the components of the system. Note especially the way in which the variable errors of the components accumulate. They do not add directly, but add according to their squares.

Squared σ's appear so frequently in statistical work that statisticians have a special name for them—variances. As we have already seen, however, the term "variance" is also used by instrument makers in a slightly different sense. This confusion of terminology is unfortunate and the reader should be careful to differentiate between the two meanings. Throughout the rest of this paper, the term variance will be used in the statistical sense to refer to variable errors measured in terms of σ^2.

Examples of the Accumulation of Variable Errors. Equation 22 is an extremely important one for our purposes. It does two things: (a) it gives us some extremely useful information about the way errors accumulate in a system, and (b) it enables us to analyze the magnitude of errors in certain parts of our system, if we know certain other errors in the system.

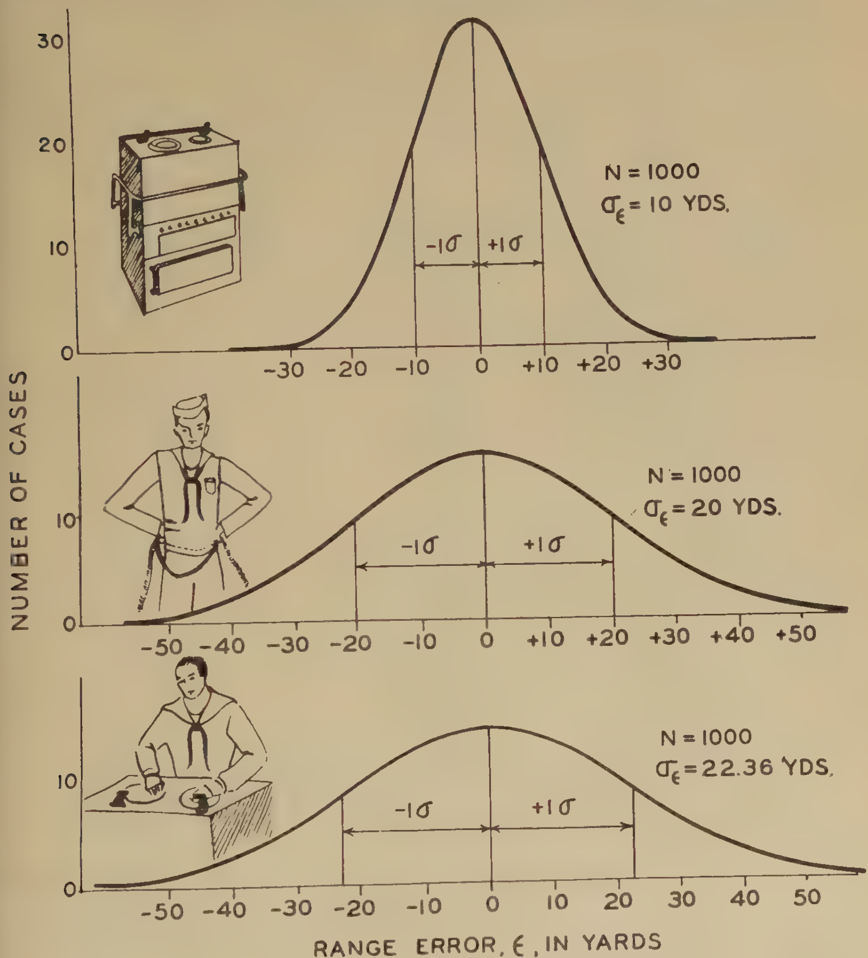
To illustrate how errors accumulate, let us assume a realistic example that might arise in an analysis with a radar indicator. The uppermost curve in FIGURE 7 is a distribution of 1,000 errors contributed to the final range readings by the radar itself. These errors include all sources of inaccuracy inherent in the radar system. We have postulated here a standard deviation of 10 yards.

Now, let us further assume that the human error in operating the radar indicator is equal to 20 yards; that is to say, on the average, the operator is twice as inaccurate as the machine. This is shown by the middle curve in FIGURE 7. When both sources of error are combined, the result is shown by the lowest curve in FIGURE 7. In short, when we accumulate both the inherent errors of the machine and the inherent error of the operator, the resultant variable error is equal to 22.36 yards.

This sort of accumulation of errors in a system has extremely important implications. In the first place, we notice that, when errors accumulate in this way, the machine's errors (the source of the smaller errors) amount to relatively very little. We have increased the variable error of the man from 20 yards to only 22.36 yards by adding in the error of the machine. This situation may be restated in a slightly different way: If we were able to eliminate completely the inherent error of the machine, we would reduce the variable error of the final range readings by only 2.36 yards. This means, in short, that we can make our greatest contribution to increasing the accuracy of the man-machine combination in this situation, not by worrying about the accuracy of the machine, but rather by increasing the inherent accuracy of the operator. We are likely to get much more for our money if we work on the man.

In the above illustration, it was assumed that the error of the man alone was twice as great as that of the machine alone. It is interesting to see what happens as this differential is increased. If the variable error of the man is 30 yards and the variable error of the machine is still 10 yards (a

ratio of 3 to 1), the variable error of the man and machine together is only 31.62 yards. The addition of the machine-error to the man-error in this case has increased the total error by 1.62 yards, or five per cent. If the variable error of the man is 50 yards and the error of the machine still 10



$$\sigma_{\epsilon_T} \doteq \left[\sigma^2_{\epsilon_{MACH}} + \sigma^2_{\epsilon_{MAN}}\right]^{\frac{1}{2}}$$

FIGURE 7. An illustration of how errors accumulate in a simple man-machine system. The uppermost distribution shows 1,000 errors made by a radar; the middle distribution 1,000 errors made by a radar operator; and the lowest distribution 1,000 errors of the operator and radar together.

yards (a ratio of 5 to 1), the variable error of the man and machine is 50.99 yards. In this case, adding the error of the machine to that of the man has increased the total error of the combination by roughly one yard, or two per cent. To state it another way, if we could make a perfect machine

for this combination, we would reduce the final variable error by only two per cent. FIGURE 8 shows what percentage of the total variable error is accounted for by the smaller of two component sources of error. Notice how rapidly the contribution of the smaller source drops off as the difference between the magnitudes of the component errors increases.

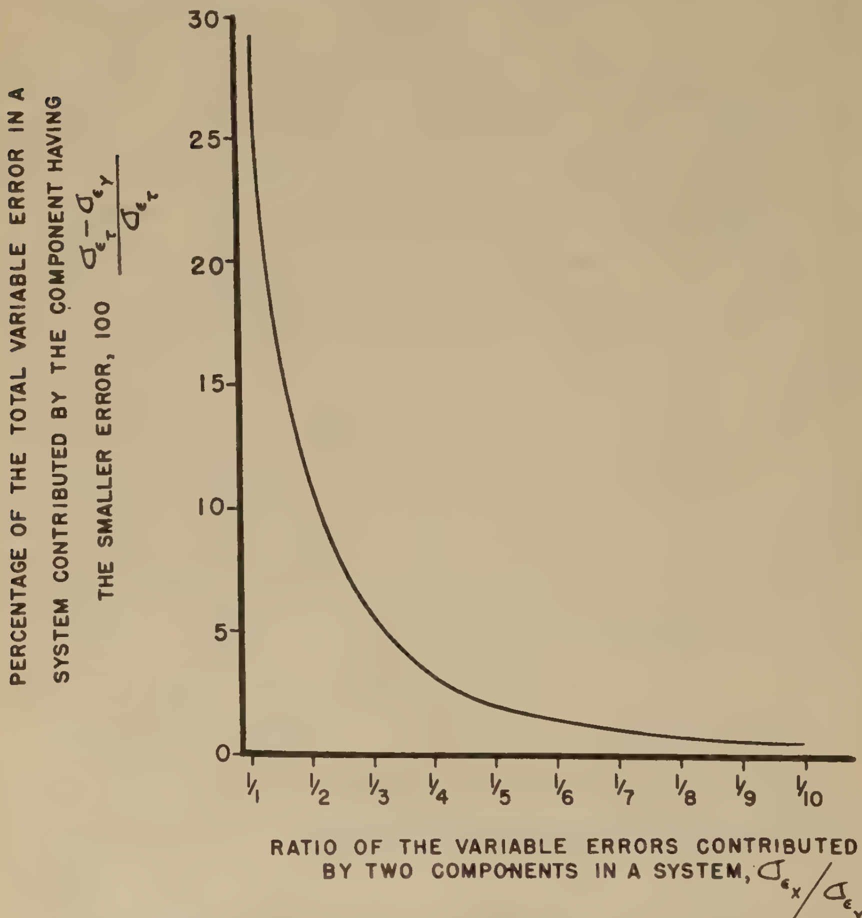


FIGURE 8. Showing what percentage of the total variable error is contributed by the smaller of two component sources of error.

The moral of this story should be clear. If at one point in our system there is an instrument or an operation which has a low inherent error, and if, further, in another location in the system, there is an operation or instrument which is relatively more inaccurate, it is not economical to attack the operation which has the low source of error, since its contribution to the total or resultant error is much smaller than we might at first suppose. Remember that it is not the addition of errors but the addition of squares of errors which make up the final result.

We can illustrate these concepts of the accumulation of errors by an industrial example. An industrial statistician was assigned to a production line manufacturing bushings. He picked 20 bushings at random from the production line and had them measured in a laboratory with such extreme precision that he could be sure of these measurements to the fourth decimal place. These measurements are listed in TABLE 2 as the true outside diameters. At the same time, an inspector measured each of the bushings with a vernier micrometer, using his normal inspection procedure. He made errors* in measuring these bushings, as shown in the second column of TABLE 2. The third column of this table gives the algebraic sums of the

TABLE 2

AN ILLUSTRATION OF ACCUMULATION OF ERRORS IN MEASUREMENTS OF THE OUTSIDE DIAMETERS OF BUSHINGS (ALL MEASUREMENTS ARE IN INCHES)

	True outside diameter (x)	*Errors of measurement* (ϵ)	*Outside diameter reported* ($x + \epsilon$)
	2.0039	+0.0005	2.0044
	2.0014	+0.0009	2.0023
	1.9980	−0.0006	1.9974
	2.0000	+0.0003	2.0003
	1.9973	+0.0008	1.9981
	1.9996	−0.0002	1.9994
	2.0010	−0.0007	2.0003
	1.9999	+0.0007	2.0006
	2.0003	0.0000	2.0003
	2.0037	−0.0004	2.0033
	2.0021	+0.0002	2.0023
	2.0006	0.0000	2.0006
	1.9976	+0.0001	1.9977
	1.9978	−0.0001	1.9977
	2.0006	+0.0006	2.0012
	1.9943	+0.0002	1.9945
	1.9993	+0.0004	1.9997
	2.0016	+0.0002	2.0018
	1.9970	+0.0003	1.9973
	2.0005	+0.0003	2.0008
Mn.	1.9998	+0.0002	2.0000
σ	0.00227	0.00042	0.00230

first two columns. The third column, in short, is the series of measurements which the inspector reported to the statistician. Thus, the first bushing had a true diameter of 2.0039″, the inspector made an error of +0.0005″, so his report to the statistician was a measurement of 2.0044″. Similarly, the second bushing had a true diameter of 2.0014″, the inspector's error in reading the micrometer was +0.0009″ so the report was a measurement of 2.0023″. Now, let us take a closer look at what has happened.

The 20 bushings in TABLE 2 had a mean diameter of 1.9998″. The inspector had a mean error (his constant error) of +0.0002″ in using the

* It is worth repeating that the human error in using precision gauges, micrometers, and calipers is considerably greater than most people expect. Lawshe and Tiffin[7] found that, in general, readings were best on the inside micrometer, which had to be read to ±0.001″, and poorest on the inside caliper and 6″ micrometer, which had to be read to ±0.002″. Readings were also very inaccurate on the 2″ and 6″ vernier micrometers when they had to be read to ±0.0001″.

micrometer, *i.e.*, he tended to read a little too high. The mean diameter reported to the statistician is exactly equal to the sum of these two means. This is an illustration of equation 6.

Now look at the variable errors in TABLE 2. If we add the σ of the true measurements (0.00227) to the σ of the inspector's errors (0.00042), we do not get the σ of the reported measurements (0.00230). The sum is 0.00269 and is about 17 per cent too big. If we use equation 22, however, we get:

$$[(0.00227)^2 + (0.00042)^2]^{\frac{1}{2}} = 0.00231.$$

The figure of 0.00231 checks within less than one per cent of the σ of the reported measurements, and would have checked exactly if the correlation had been exactly zero.

In the above illustration, the human error happens to contribute very little to the final variability. The reader can make up his own examples to amplify the point still further. One important implication for engineering psychology is the following: there is no reason to increase the inherent stability of instruments to the absolute limit if the dials and scales on these instruments are so constructed that a human operator makes large errors in reading them. The following quotation from Schlink[8] is pertinent to this problem: "It is often found that particular measuring instruments are given a sensitivity far higher than warranted in the face of the error obtainable in reading and resulting from the variance present. Similarly, the graduation of instruments is often found to be far closer than the large amount of the variance justifies. Care should be taken in the design of measuring instruments that the units of graduation and the openness of the scale are not out of all proportion to the effective reproducibility of reading possible."

The Accumulation of Constant and Variable Errors. It is also instructive to derive a single formula to show how the constant and variable errors combine in a system. Essentially, we want an expression for ${}_0\sigma_{\epsilon_T}$ in terms of σ_{ϵ_T} and M_{ϵ_T}. In an earlier derivation, equation 12, we found that

$$N^2\sigma^2_{\epsilon_T} = N\Sigma\epsilon^2_T - (\Sigma\epsilon_T)^2. \tag{26}$$

Hence,

$$\sigma^2_{\epsilon_T} = \frac{\Sigma\epsilon^2_T}{N} - \left(\frac{\Sigma\epsilon_T}{N}\right)^2 \tag{27}$$

and

$$\sigma^2_{\epsilon_T} = \frac{\Sigma\epsilon^2_T}{N} - M^2_{\epsilon_T}. \tag{28}$$

Using the identity for ${}_0\sigma_\epsilon$ given in equation 3 gives:

$$\sigma^2_{\epsilon_T} = {}_0\sigma^2_{\epsilon_T} - M^2_{\epsilon_T} \tag{29}$$

or

$${}_0\sigma^2_{\epsilon_T} = \sigma^2_{\epsilon_T} + M^2_{\epsilon_T} \tag{30}$$

$${}_0\sigma_{\epsilon_T} = [\sigma^2_{\epsilon_T} + M^2_{\epsilon_T}]^{\frac{1}{2}}. \tag{31}$$

Equation 31 states essentially that the variable error around the zero error or true value (the true range in the case of radar) is equal to the square root of the squared constant error plus the squared variable error around the constant error. It bears a striking resemblance to equation 22, which shows how component variable errors accumulate to make up the total variable errors in a system.

It is an important formula in that it provides some estimate of the relative importance of the constant and variable errors in a system. Exactly the same argument which applied to equation 22 holds here. So long as the constant error, $M_{\epsilon T}$, is small as compared with the variable error, $\sigma_{\epsilon T}$, its contribution to the total error of the system is negligible. A constant error in a system means that the readings will be biased, *i.e.*, the average of a

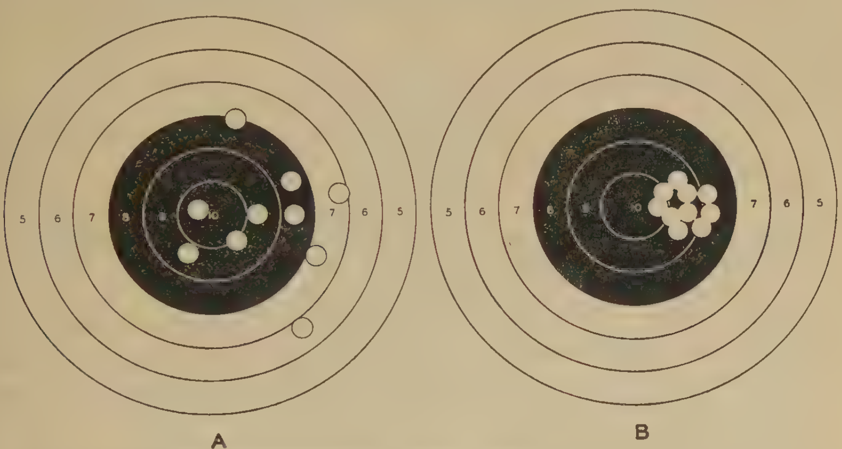


FIGURE 9. Same target patterns as illustrated in FIGURE 1, except that both have a small constant error of the same magnitude. Notice that a correction in A's sights would not increase his score appreciably because of the magnitude of his variable errors. When the variable errors are small, as in the case of B, the same constant error becomes much more important.

large number of readings will be too high or too low by some amount. But so long as the ratio $M_{\epsilon T}/\sigma_{\epsilon T}$ is $\frac{1}{3}$ or less, the contribution of the constant error to any single reading will, on the average, be unimportant (*cf.* FIGURE 8).

This conclusion is of considerable practical importance in the case of radar, although its implications are not generally understood by radar engineers. Some of them spend great amounts of money and time in calibrating radar equipment, *i.e.*, in attempting to eliminate constant errors, without at the same time concerning themselves with the instability of the equipment as reflected in the variable errors.

Much the same argument applies to other situations. A slight error in the adjustment of a rifle sight is of trivial consequence for an inherently unsteady rifleman. For the expert rifleman, however, it may be a deciding factor (*cf.* FIGURE 9) if the constant error approaches his variable error in magnitude.

Analysis of Systems Errors

However important equations 6, 22, and 31 are for assaying the relative importance of various component errors, they serve a much more useful function in enabling us to measure the amount of error in certain parts of systems when certain other errors are known. Perhaps the best way to demonstrate their usefulness is by specific examples.

One type of problem encountered in radar research concerns the measurement of the variable error of a radar when the true ranges of the targets cannot be measured. The solution to this problem can be reached if two radar indicators of the same type are employed simultaneously. Both radar indicators are used to range on the same series of targets. A range report from the first radar, R_1, is a combination of the true range of the target, R_T, plus the error of the radar indicator and its operator, ϵ_1. Thus:

$$R_1 = R_T + \epsilon_1. \tag{32}$$

Similarly, a range report from the second radar, R_2, is:

$$R_2 = R_T + \epsilon_2. \tag{33}$$

Even if we have only the range reports from the two radars, we can still discover more about the inherent variability of one radar system by performing a few algebraic manipulations. First, let us find the differences between corresponding range reports from the two radars. Thus:

$$R_1 - R_2 = (R_T + \epsilon_1) - (R_T + \epsilon_2) = \epsilon_1 - \epsilon_2. \tag{34}$$

This formula states that when two radars have ranged on the same target, the difference between their range reports is equal to the difference between the errors inherent in the two radars and their operators.

If such differences are obtained on a large number of targets, we may write:

$$\sigma_{R_1-R_2} = \sigma_{\epsilon_1-\epsilon_2} = [\sigma^2_{\epsilon_1} + \sigma^2_{\epsilon_2}]^{\frac{1}{2}}. \tag{35}$$

The value on the left of the equal sign is the only value we know. In this instance, however, it is reasonable to assume that the variable errors of the two radars are of about the same order of magnitude so that:

$$\sigma_\epsilon = \sigma_{\epsilon_1} = \sigma_{\epsilon_2}. \tag{36}$$

Thus:

$$\sigma_{\epsilon_1-\epsilon_2} = [2\sigma^2_\epsilon]^{\frac{1}{2}} \tag{37}$$

and

$$\sigma_\epsilon = \frac{1}{\sqrt{2}}\sigma_{\epsilon_1-\epsilon_2} = \frac{1}{\sqrt{2}}\sigma_{R_1-R_2}. \tag{38}$$

To pick specific numbers, if the σ of the differences between range reports on the two radars is 20 yards, the variable error of the range reports from one radar is 14.1 yards.

It is important to note in this example that it is impossible to determine the magnitude of the constant errors of the two radars. Let us assume, for example, that the mean difference, $M_{R_1-R_2}$, was -10 yards. This tells us that there is some constant error, either physical or psychological or both, in the operation of one or both of the radars. But we cannot discover the magnitude of the constant error of one radar because one might be off by 100 yards, the other by 90; or one might be off by -30 and the other by -40 and the constant difference would be the same.

One of the most useful applications of these techniques is an extension of the problem we have just dealt with. It involves the simultaneous determination of the variable error of three different radars, each ranging on identical targets which are at unknown distances. By the application of the equations in the same manner as above (*cf.* equation 35), it is possible to set up three simultaneous equations:

$$\sigma_{R_1-R_2} = [\sigma_{\epsilon_1}^2 + \sigma_{\epsilon_2}^2]^{\frac{1}{2}}; \tag{39}$$

$$\sigma_{R_1-R_3} = [\sigma_{\epsilon_1}^2 + \sigma_{\epsilon_3}^2]^{\frac{1}{2}}; \tag{40}$$

and

$$\sigma_{R_2-R_3} = [\sigma_{\epsilon_1}^2 + \sigma_{\epsilon_2}^2]^{\frac{1}{2}}. \tag{41}$$

The quantities to the left of the equal signs are the only ones known, but there are three equations to solve for three unknowns: σ_{ϵ_1}, σ_{ϵ_2}, and σ_{ϵ_3}. Needless to say, the problem is easily solved when set up in this fashion.

Notice, in this example, that it is no longer necessary to make any assumptions about the variable errors of any of the radars. When only two radars are used, it is necessary that they be the same kind of radar and it is also necessary to assume that the variable errors of the two radars are of the same order of magnitude (equation 36). Neither of these conditions must be met when three or more radars are used.

The solution to the three-radar problem also provides a solution to the problem of estimating the magnitude of the error contributed by a target generator of some sort. If two radars are operated from the same target generator, we can use the same kinds of simultaneous equations as 39, 40, and 41. The only difference is that the range set into the target generator is substituted for the range reported from one of the radars. Thus, if we let R_G represent the range set into the generator, the equations are:

$$\sigma_{R_G-R_1} = [\sigma_{\epsilon_G}^2 + \sigma_{\epsilon_1}^2]^{\frac{1}{2}}; \tag{42}$$

$$\sigma_{R_G-R_2} = [\sigma_{\epsilon_G}^2 + \sigma_{\epsilon_2}^2]^{\frac{1}{2}}; \tag{43}$$

and

$$\sigma_{R_1-R_2} = [\sigma_{\epsilon_1}^2 + \sigma_{\epsilon_2}^2]^{\frac{1}{2}}. \tag{44}$$

Once the basic concepts involved in the accumulation of error variances are understood, it is possible to go on almost indefinitely with solutions to a great variety of practical problems. Perhaps one more illustration of a slightly different sort will suffice. In the above solutions, the error contributed by the radar operator has been combined with the inherent error of the radar. For many purposes, it is necessary to determine how much

of the error is contributed by the radar operator in adjusting his electronic range marker on the radar scope. Such an estimate may be made by having the operator make two determinations of the range of a target in quick succession. The standard deviation of the differences between pairs of such reports indicates the amount of error the operator makes in bisecting the target, manipulating the electronic aids, *etc.*

Discussion

The statistician will recognize that the methods discussed in this paper are the first step in a statistical method of analysis called the analysis of variance. The analysis of variance actually goes one step further than do the techniques discussed in this paper. Having partialed the variance of the total process into its component errors, this technique then goes on to apply statistical tests of significance to these partial variances. The details of this procedure are beyond the scope of this paper, but the interested reader is referred to recent texts in the field of industrial experimentation which discuss them in great detail.[3, 6]

Since these basic equations may be mistrusted for certain problems, it should be pointed out that there are no hidden assumptions in equation 21, and that there is only one explicit assumption (*i.e.*, that of zero correlation between component errors) in equation 22. In particular, no assumptions regarding the normality of the distributions of errors are implicit in any of these derivations. The equations are valid for skewed, rectangular, or other irregular types of distributions. If the errors are not distributed normally, however, the standard deviation cannot be used to infer the percentage of errors which fall within certain limits.

Fortunately, most sets of errors, in both physical and biological phenomena, appear to be normally distributed. Whenever this situation obtains in a system, the standard deviation can be easily interpreted in terms of the average deviation or other measures of dispersion. The average deviation is defined in statistical terms as the average discrepancy between a set of values and the mean value. It indicates, in short, the average discrepancy of a set of values irrespective of the direction of the error. It is more easily understood by the lay person because it indicates how far off a set of values will be on the average. The formula for an average deviation is:

$$A.D. = \frac{\Sigma |\epsilon - M_\epsilon|}{N}. \tag{45}$$

In his discussion of probability as applied to errors in precision instruments and mechanisms, Whitehead[10] has derived an equation similar to equation 22 in this paper. His equation, however, is expressed in terms of the average deviation, or the mean error, as he refers to it. He is careful to point out, however, that his equation is valid only if the errors can be shown to be normally distributed. The equations derived in this paper are of more general applicability, since they do not make any such assumptions.

Bibliography

1. Alger, P. L. 1941. The importance of the statistical viewpoint in high production manufacturing. J. Am. Stat. Assoc. **36:** 50–52.
2. Behar, M. F. 1940. The "accuracy" and other measuring properties of temperature instruments. Instruments **13:** 240–242.
3. Brownlee, K. A. 1947. Industrial Experimentation. Chemical Publishing Co. Brooklyn, New York.
4. Coakley, J. D. 1947. Human influence on the product of automatic machines. Unpublished research report. Psychological Corporation, New York.
5. Eisenhart, C., M. W. Hastay, & W. A. Wallis (Ed.) 1947. Selected Techniques of Statistical Analysis. McGraw-Hill, New York.
6. Freeman, H. A. 1942. Industrial Statistics. John Wiley & Sons, New York.
7. Lawshe, C. H. Jr. & J. Tiffin. 1945. The accuracy of precision instrument measurement in industrial inspection. J. Appl. Psychol. **29:** 413–19.
8. Schlink, F. J. 1919. Variance of measuring instruments and its relation to accuracy and sensitivity. Bull. Bur. Stand. Wash. **14:** 741–764.
9. Smith, E. S. 1947. Control Charts: An Introduction to Statistical Quality Control. McGraw-Hill. New York.
10. Whitehead, T. N. 1934. The Design and Use of Instruments and Accurate Mechanisms. The Macmillan Company. New York.
11. Yule, G. U. & M. G. Kendall. 1937. An Introduction to the Theory of Statistics. (11th Ed.) Charles Griffith & Co., Ltd. London.

BETTER COCKPIT LIGHTING

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Aircraft cockpit lighting has received a great deal of attention in the last few years, despite all of which, present methods of lighting are not good enough. The search goes on, and I think it will continue to go on just as long as we fail to ask ourselves and answer the question, "Better cockpit lighting under what conditions?" The question was asked once during World War II. The answer was, "For fighter aircraft operating at night." It was required that: (a) the pilot have maximum vision outside the aircraft consistent with readability of the instruments; (b) the lighting installation be consistent with military security. These requirements were reasonably well achieved through the use of indirect red light, the intensity of which was controllable, and through a 30-minute period of dark adaptation.

This is a rigorous requirement and it was assumed that it would, therefore, prove satisfactory for other military aircraft including transports. No one can deny the value of a standard lighting system for all types of aircraft. The continued search for better lighting implies, however, that the solution for the night fighter is not a general solution. I think we might have learned this less expensively and with more insight if we had studied the way in which the fighter lighting system was engineered, the way it met the criteria of a good lighting system.

It must be obvious that a good many compromises must be made in a system in which control is attempted on (1) illumination of object and background; (2) illumination of surroundings; (3) glare from light sources; (4) reduction in contrast due to specularity; (5) glare due to reflected light; (6) shadows; (7) illumination ratio; (8) spectral distribution of radiant power; and (9) contrast. It is not likely that the compromises that satisfy one situation are necessarily going to satisfy another. The Army, for example, attempted to install the Navy indirect red system in a B-17 mockup but found the variations of brightness so great that the method was abandoned. The inflexibility of the Navy system is most forcibly illustrated, however, when it is noted that even minor changes in the location or size of instruments plays havoc with the effectiveness of the installation.

But these are not the only criteria that must be met. A system for cockpit lighting must also take into account:

(1) *Pilot acceptability.* A lighting system, no matter how effective theoretically, must be accepted by flight personnel or it will not be used. To this end, the Navy undertook an extensive training program for night fighter pilots.

(2). *Visual sensitivity.* The threshold of sensitivity for objects outside the cockpit will depend on the mission. Thirty minutes of dark adaptation and minimum red cockpit lighting are hardly justified for non-military night operations, since targets, such as obstructions and traffic, are illuminated.

*The opinions or assertions contained herein are the private ones of the writer and are not to be construed as official or as reflecting the views of the Navy Department or the naval service at large.

(3) *Instrument design.* Many of the lighting difficulties we face today exist because of the type of instrument display employed. If we find that a pilot can get along with relative data on engine performance, for example, the simpler display for engine data makes the task of lighting easier too.

(4) *Servicing requirements.* A lighting system will not be entirely acceptable if it introduces extensive servicing problems. The Navy indirect red with cover panel and plastic interpanel did a fair lighting job, but it was an installation and servicing nightmare.

(5) *Fatigue.* A satisfactory lighting system must not contribute unduly to visual fatigue. Poor control of glare, illumination ratio, spectral distribution, *etc.*, increase visual fatigue.

(6) *Orientation.* Lighting contributes to the pilot's frame of reference and is a factor of unknown importance.

(7) *Daylight use.* No lighting system can be considered satisfactory if, in achieving its goal, it contributes to daylight cockpit problems. A system designed to reduce glare from reflected light sources during night operation may contribute to the glare problem when the sun is over and behind the pilot's head.

It seems obvious that, because of the large number of variables, a standard (inflexible) cockpit lighting system must depend on the acceptability of the same compromises. This is not likely to be achieved. It should be possible, however, to formulate a general principle of lighting that has sufficient flexibility to accommodate the varying requirements for different aircraft and operational needs.

A comprehensive study of cockpit lighting requirements is necessary before a sound principle of cockpit lighting can be formulated. Short of such an analysis, we can only pretend to know what such a system might be. An examination of the four systems of cockpit lighting: (1) indirect lighting; (2) fluorescent lighting; (3) flood lighting; and (4) a combination of flood and fluorescent lighting, is not helpful in this respect, for none of the systems have been adequately and systematically exploited.

Indirect lighting, the system sponsored with considerable success for fighter aircraft by the Navy, is presently the system most favored. It has, however, the least potential of all the systems for further development. I am of this opinion because it appears impossible to prevent glare from edges around the instruments, particularly in multiplace cockpits. The arithmetic (Fresnel's Law) involved in computing illumination in indirect systems is so complex that solution is by trial and error. Such a system becomes the work of an artist and is incompatible with careful planning in the drafting room. The effects of minor changes in design or layout cannot be anticipated and call for additional periods of trial and error.

Flood lighting, on the other hand, lends itself easily to computation and drafting board analysis. The illumination of panel area between instruments minimizes the floating observed in the other systems. The chief disadvantages are difficulty in achieving a minimum illumination ratio and reflected glare. Flood lighting deserves renewed attention, especially in association with fluorescent lighting.

Fluorescent lighting, as we know it in aircraft today, is by far the most inadequate system. This is inexcusable, for better phosphors, filters, and ultraviolet sources are available. The principle disadvantages of the present system are inadequate intensity range; poor illumination ratio; inadequate spectral characteristics; floating (apparent motion); and inadequate filters and ultraviolet sources. The outstanding characteristic of fluorescent lighting is, of course, its extremely high contrast. Relatively little effort should produce a much better fluorescent system than is now available.

Dual lighting, or the combination of flood and fluorescent lighting, has been used by the British. They have reported that satisfactory installations can be made in almost any aircraft without too much difficulty. I have carefully inspected such a system and must admit it is probably the most adequate yet developed.

The facts presented are quite elementary, but I believe they indicate that improved cockpit lighting can be achieved most quickly if it is recognized that: (1) no standard (inflexible) lighting system appears possible; (2) a general principle of cockpit lighting seems attainable; (3) a comprehensive study of cockpit lighting requirements for the various types of aircraft and operational situations is necessary; (4) indirect lighting, the method now in favor, has the least promise of providing a general principle of lighting; and (5) fluorescent, flood lighting, and a combination of the two have not been intensively exploited and deserve more serious attention.

THE BASIC PATTERN OF HUMAN LOCOMOTION

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The efficient management of normal motor activities and the substitution of prosthetic devices for the normal mechanisms depend on an understanding of the fundamental factors which underlie human movement. Locomotion is similar to other movements executed by the body in that its characteristics are determined in part by constant structural features and in part by factors which are under voluntary control.

The Locomotor Mechanism. The constant structural features of the human mechanism which limit the possible types of movement include: the dimensions and configurations of the bones; the restriction of movement in the joints; and the distribution of mass in the members. Although these features vary somewhat from individual to individual and undergo marked transformations during infancy, they are not under voluntary control and must be accepted by the individual as constant elements of his motor mechanism.

The muscles contrast with the skeleton and joints in being susceptible of voluntary control. It is through determining the response of the muscles that the individual has his only direct means of influencing his locomotor progress. This control can only be exercised by changing the number of fiber groups active at any one time, not by changing the quality of their contraction. The nervous system has the formidable task of taking into account the numerous factors which affect the response of the muscle. Among these factors are the instantaneous length of the muscle fiber, its state of fatigue, rate of shortening, and length of lever arm. Impulses must then be sent to the proper number of fibers to produce the moment of force which is necessary.

Fundamental Features of Locomotion. The primary objective of locomotion is to move the body from one position to another. Although the body usually finishes a movement with its various parts in a configuration similar to that which they possessed when the movement started, the very nature of the locomotor mechanism involves relative movement of the parts during the process of locomotion.

Paramount in importance among the relative movements is the oscillation of the lower extremities. The vast majority of locomotor movements are based on alternating periods of support, first by one extremity and then by the other. In order to be in proper position at the appropriate time, one extremity must usually be swinging forward with respect to the common center of gravity of the body while the other is swinging backward. When this is accomplished, as it can be, with equal but opposite angular momentum for the two extremities, the oscillation is independent of the movement of the common center of gravity and does not contribute to the reaction of the ground. These relative movements do, however, involve the expenditure

of muscular energy and are major factors in determining the metabolic cost of locomotion.

Although the oscillation of the extremities is a necessary concomitant of locomotion, the primary objective is the movement of the body as a whole. Progress toward this objective is most adequately measured by the movement in space of the center of gravity of the whole body. This center of mass is not permanently situated at any one anatomical position but varies in location with the relative movement of the parts of the body.

In contrast to symmetrical accelerations of the extremities, any acceleration of the center of mass of the body must be produced by a force external to the body. The external forces which are of major importance are only two in number. One is the force of gravity and the other is the force exerted by the ground on that part of the body momentarily in contact with it. These are the forces which the body must regulate if locomotion is to be controlled. Other external forces, such as wind resistance, are of secondary importance.

The Control of Locomotion. The force of gravity is constant, but the moment exerted by gravity on each of the links of the mechanism varies with the relative positions of the parts of the body. Control over these moments can, therefore, be exercised only indirectly, by introducing accelerations which influence the subsequent positions taken.

The control which the body can exert on its locomotion at any particular moment must consequently be reflected in the ground reaction. This may be illustrated by considering a man running, using the data published by Elftman (1940). In FIGURE 1, the subject is shown at the left in the position in which he found himself after completing a parabolic trajectory through the air and establishing contact with the ground through the ball of his right foot. At the right, he is again leaving the ground for another free flight through the air. The position of the center of mass of the body is shown and its linear momentum is indicated by means of arrows.

The problem which faces the runner when his foot makes contact with the ground is apparent. If he wishes to continue running he must not only oscillate his lower extremities so as to bring them into the second position shown; he must also produce the accelerations which will result in the indicated change in his momentum. And this he must do against the constant downward acceleration of gravity.

The ground reaction which must be produced in order to provide a proper solution for this problem is shown in FIGURE 2. The vertical component of this reaction is indicated in two parts. The first, labeled G, is the reaction to gravity and is consequently equal to the weight of the body. The second part, V, must be sufficient to produce the upward acceleration demanded by the change in linear momentum as shown in FIGURE 1. The vertical component of the reaction is consequently prescribed within narrow limits.

The horizontal component of the ground reaction is determined in a less direct fashion. The important consideration here is the effect which the ground reaction will have on the angular acceleration of the body. It is

apparent, from FIGURE 2, that the perpendicular distance from the center of gravity to the interrupted line which represents the line of action of the ground reaction is the lever arm for this angular acceleration. Since the angular velocity of the body is small and must, in any case, oscillate about zero, the line of action tends to pass in the vicinity of the center of gravity. With the point of application of the reaction restricted to the area of contact of the foot with the ground, the inclination of the reaction is determined. In conjunction with the vertical component, the inclination fixes the value of the horizontal component.

Having found out, in this way, what ground reaction is necessary, we

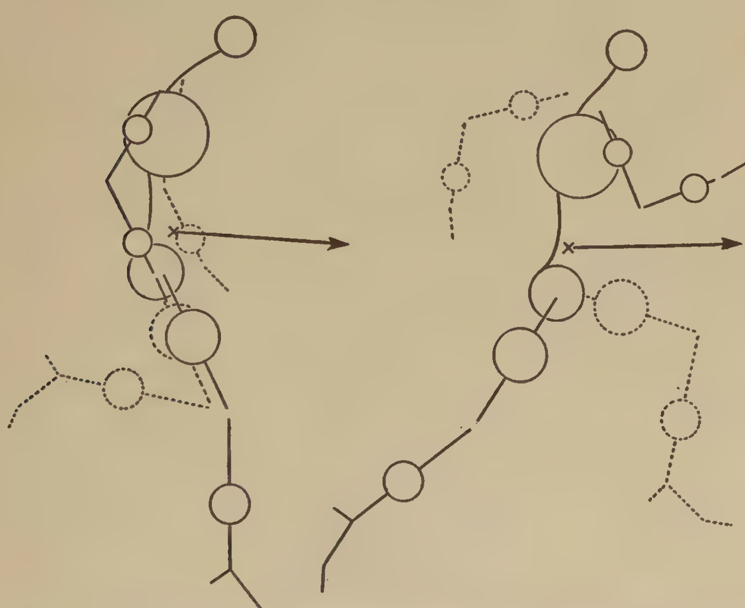

FIGURE 1. The position of the body in running at the beginning and the termination of one contact with the ground. The arrows originate at the center of gravity of the body and indicate the linear momentum.

must next inquire what means the body can use to elicit this reaction. We know that the body exercises its control over locomotion by regulating the muscles. The ground reaction is produced by calling into activity the proper number of fibers in the muscles spanning the ankle, knee, and hip joints so as to produce the muscle moments of force symbolized by A, K, and H in FIGURE 2. If the limb were free of inertia, each of these moments would be equal to the magnitude of the resultant reaction, R, times the perpendicular distance from the line of action to the axis of the joint concerned. The actual value of the muscle moments may be computed by modifying this first approximation by taking into account the mass and acceleration of each link in the system.

Application to Walking. Some of the basic features of walking are illustrated in FIGURE 3. The successive positions of the lower right extremity

and of the center of gravity of the whole body are shown for the most classic step in the history of locomotion, that described by Fischer (1899). Superimposed upon this representation of the positions of the lower extremity are the ground reactions and their lines of action, indicated by interrupted lines, for positions B through F. The points of application of the ground reaction were found from Fischer's data by Elftman (1939b). The magnitude of the ground reaction is indicated by the dotted line, RG, which corresponds to a vertical component equal to the weight of the body.

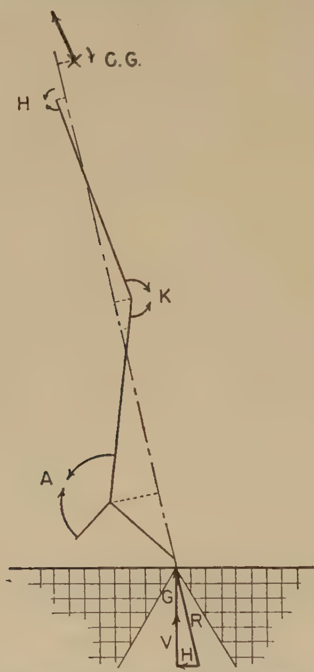

FIGURE 2. Factors determining the ground reaction. C.G.—center of gravity of the body, with arrows indicating the linear and angular accelerations. H, K, and A—moments of force produced by muscles. R—resultant ground reaction, with its components G, V, and H for the reaction to gravity, for vertical acceleration, and for horizontal acceleration. The cross-hatched area shows the limitations placed upon the inclination of the ground reaction by the coefficient of friction.

The phases of the step which are illustrated in FIGURE 3 represent critical periods in the locomotor process. From A to B the body is supported by both lower extremities and receives upward acceleration, which continues after the lower right extremity takes over unshared control at B. The vertical acceleration decreases until it reaches zero at C, as shown by the fact that the vertical component of the ground reaction is equal to the weight of the body. From C to E the body undergoes downward acceleration, remotely comparable to the free-flight phase of running. The intermediate phase D marks the time when the horizontal component of the ground reaction passes through zero in the process of changing from a backward to a forward direction. After phase E, the acceleration is again upward, due to

the right extremity alone until F, at which time the left extremity contacts the ground.

The influence of the ground reaction on the angular acceleration of the body as a whole is shown by the magnitude of the reaction and the distance which separates its line of action from the center of gravity of the body. In FIGURE 3, it is apparent that the counter-clockwise acceleration during the

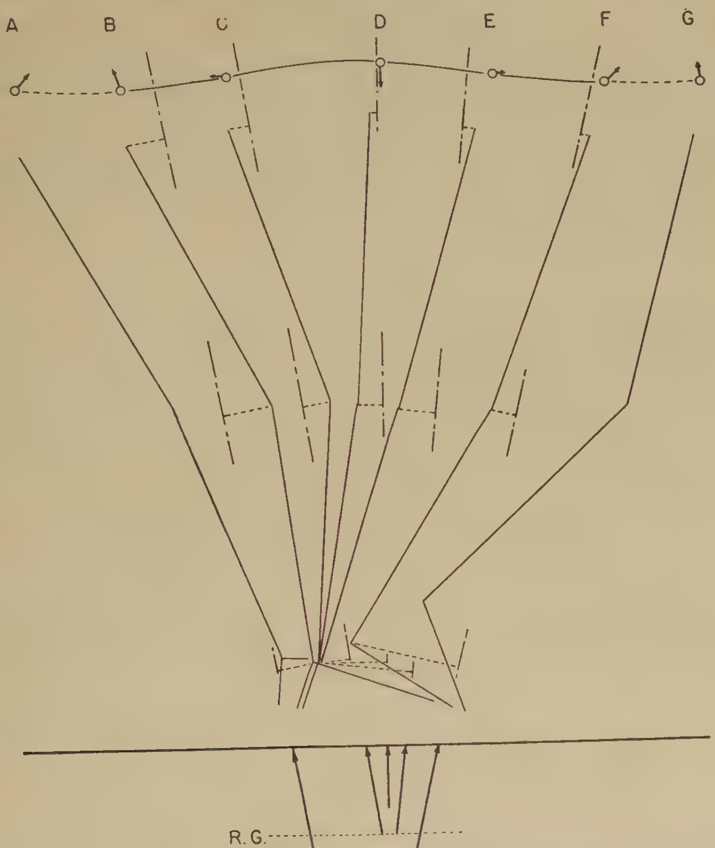

FIGURE 3. Ground reaction and stick diagram analysis of walking. The positions of the lower right extremity are shown for phases of one step, chosen according to criteria explained in the text. The position of the center of gravity of the body is shown for each phase by a circle, with an arrow indicating the instantaneous linear acceleration. The ground reaction is shown for phases B through F with the lines of action projected through the diagram by means of interrupted lines. The dotted line RG indicates a vertical component equal to the weight of the body.

first part of the step is balanced by a clockwise acceleration later. It is also evident that the backward linear acceleration of the early phases is balanced by a forward acceleration after phase D.

The muscular moments about the ankle, knee, and hip joints may also be estimated, to a first approximation, from this diagram. If the lower extremity were free of inertia, an exact measure of these moments would be obtained by multiplying the magnitude of the ground reaction and the

perpendicular distance between its line of action and the axis of the joint concerned. The actual muscle moments can be obtained by adjusting these approximations for the masses and accelerations of the successive members from toe to hip. Since over 80 per cent of the body mass is beyond the confines of this extremity, the adequacy of the first approximation for many problems is evident.

Diagrams, such as that of FIGURE 3, have proven of practical value in the solution of actual problems concerned with walking. The information needed for their construction can be obtained from photographic records of the movements, coupled with force plate measurements of the ground reaction (Elftman 1938, 1939a). The marked improvements in methods for obtaining accurate ground reaction and photographic data, developed by Eberhart at the University of California, increase the feasibility of this type of analysis as a preliminary approach to a problem bristling with complicated detail.

Summary

The basic pattern of human locomotion is dependent on the structural characteristics of the human body, with regard both to dimensions of members and restraint of movement in joints. The primary objective of locomotion is to transport the body from one position to another, using the lower extremities in coordinated oscillation as the effective locomotor mechanism. It is his ability to control the force exerted by muscles which gives the individual his only primary control over locomotion. By this means, he is able to influence one of the external forces acting on the body, the reaction of the ground. It is only indirectly, by a sequence of muscular accelerations, that the position of the body and, thus, the effect of gravity can be regulated. The interplay of these factors in locomotion can be studied by a method which combines a photographic record of the movements of the body and force plate registration of the reaction of the ground.

References

ELFTMAN, H. 1938. The measurement of the external force in walking. Science **88:** 152.

ELFTMAN, H. 1939a. Forces and energy changes in the leg during walking. Am. J. Physiol. **125:** 339.

ELFTMAN, H. 1939a. The rotation of the body in walking. Arbeitsphysiologie **10:** 477.

ELFTMAN, H. 1940. The work done by muscles in running. Am. J. Physiol. **129:** 672.

FISCHER, O. 1899. Der Gang des Menschen. II Teil. Abh. K. Sachs. Ges. Wiss., Math. Phys. Cl. **25:** 1.

AN EVALUATION OF EXPERIMENTAL PROCEDURES USED IN A FUNDAMENTAL STUDY OF HUMAN LOCOMOTION*

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A critical evaluation of an experimental study of locomotion should include a consideration of the following elements. First, why is such a study undertaken and of what use will be the information obtained from it? Second, what techniques may be utilized, and what are the advantages, limitations, and shortcomings of the procedures employed? The final evaluation of an experimental procedure in respect to the abovementioned elements can only be reached after the techniques have been actually employed. Some of the techniques which we envisioned as yielding fundamental information have proved disappointing because of the failure to consider all factors before their employment. Other techniques which we felt would be of limited value were found to be singularly significant as a source of fundamental information. Because of our experience, we feel that a review of the techniques employed and a critical evaluation of the experimental procedures would prove of value to other investigators who might enter the field of human locomotion and assist in the interpretation of results from the work still in progress.

Reasons for the Study of Human Locomotion. The reasons for studying human locomotion may be divided into four main categories.

(1) The orthopedic surgeon is called upon frequently to attempt surgical procedures in order to improve the function of the locomotor system in individuals who have suffered damage to it. This includes not only fractures, but damage to joints and muscles. It is obvious that any attempted surgical procedure with any hope of success must depend upon an accurate knowledge of the functions of the parts involved.

(2) The physiotherapist has definite need of similar information in order to provide adequate treatment and proper functional training of impaired parts.

(3) When portions of the locomotor system are irreparably injured, the surgeon must rely upon external support. These supporting braces must be designed for the work demanded of them without restraining the remaining normal functions if they are to prove of value.

(4) With the loss of a part, as in the amputee, an attempt is made to replace the lost portion with a prosthesis. How poorly we have succeeded in duplicating nature is evidenced daily by the individual who is in contact with the amputee.

It is apparent that any improvement, either in surgical and physiotherapeutic procedures, or in braces and prostheses, must depend upon better knowledge of the function of the locomotor system.

* This work was done for the Committee on Artificial Limbs, National Research Council, and supported by the Veterans Administration and the Surgeon General's Office.

Information Desired From a Locomotion Study. The locomotor system of the body may be looked upon as a concatenation of articulated segments. While the displacements of the entire body may be described as translatory, these motions are achieved by the angular displacements of the segments about various axes which lie in the proximity of joints. One of the principal tasks in a study of human locomotion is to describe quantitatively these angular displacements and relate them to the movement of the entire body. An adequate description not only requires that the regular changes be measured in the three planes of space, but should also indicate the speed with which they occur.

In order for motions of translation and rotation to take place there must be an application of force, the principal sources of which are muscle action and gravity. Knowledge of the relationship between the forces acting and the resulting body movements is fundamental and important for a general understanding of locomotion. Each can be determined from the other by analytical methods, but the labor involved in studying the effect of variables, and the unavoidable inaccuracies due to necessary assumptions and limitations in the reduction of the original data, preclude such a study except on limited cases.

The techniques indicated here are considered with respect to a complete description of what happens in terms of displacements and forces to the lower extremity and the pelvis during locomotion. This involves the recording and measurement of the magnitudes, directions, and rates of change of translations, rotations, and forces with respect to three coordinate axes in space. No one technique will yield all the desired information. A variety of methods must be employed to obtain the different types of data. The number and variety of experimental procedures possible in such a study appears limited only by the facilitie and ingenuity of the investigators. The choice of a particular method, however, is dictated by such factors as simplicity of recording, ease of reduction of the data, and the accuracy of the findings.

Experimental Techniques—Displacements

Glass Walkway. Moving pictures have proved to be an excellent means of recording motion. Individually selected frames can be enlarged and the displacements measured. By simultaneously photographing a timing device, the measured displacements can be plotted as a function of time and the velocity and acceleration of selected points can be determined.

The glass walkway was designed and constructed to provide a means for the study of displacements in the three planes of space simultaneously. The use of a mirror placed below the transparent walkway and inclined at an angle of 45 degrees made it possible to record the side and bottom views of the subject with one camera, as shown in FIGURE 1. An additional camera, operated synchronously from the end of the walkway, permitted views to be obtained in the third plane of space.

The moving picture recordings were taken on 35-millimeter film at 48 frames per second. To facilitate measurements, targets, consisting of pieces of adhesive tape with round black centers, were placed upon the subject.

The target positions chosen were the approximate centers of rotation of the joints of the inferior extremity. By placing the glass walkway on a large laboratory roof, the cameras could be placed far enough from the subject (40 feet) to reduce the errors due to perspective to a neglibible amount. In the reduction of the data from projected individual frames, the location of targets was obtained with a maximum error of about one half inch. The measurement of angles was made with a universal drafting machine and an accuracy of about one degree.

FIGURE. 1. Subject with targets and ankle pin ready for glass walkway run.

Rotations about the long axes of the segments, as projected on the horizontal plane, were more difficult to determine. To measure these horizontal rotations accurately, targets were used which were fastened to the pelvis and ankle. The former consisted of an adjustable contact brace placed upon the four bony prominences of the pelvis, the anterior and posterior superior iliac spines. Anterior and posterior projections were connected to the framework, the increased displacements of which could be more accurately measured and pelvic rotations determined.

To evaluate the rotation between the body and the lower leg, a second target was attached to the ankle. This consisted of a U-shaped bracket holding two small pins, one for the medial malleolus and the other, a small adjustable screw pin, to fit onto the lateral malleolus. This device was ap-

plied to the ankle after injecting 2 per cent procaine into the skin and deeper structures. The pins entered the cortices of the bone, rigidly fixing the entire target and accurately indicating the displacements of the leg bones. A small dowel carrying a target extended horizontally from the outer side of the bracket, exaggerating angular displacements and facilitating the ease and accuracy of measurement.

An indication of the quantity and type of data obtained from the side and bottom view of a subject on the glass walkway is given in FIGURE 2. This is a reproduction of a plot made by superimposing successive frames taken by the lateral camera. Relative motions and angular changes may be

FIGURE 2. Plot of glass walkway data.

studied and quantitative data obtained for detailed consideration of rate of change.

Precautions were necessary to prevent restriction of motion by the targets used and to obtain normal walking. No apparent effects due to walking on a glass surface have been detected by direct comparison with the same subject walking on other surfaces. The glass walkway proved very effective for a simultaneous three-view study of level walking but is not applicable to a study of motion on inclines or steps.

Interrupted Lights. To achieve greater accuracy in the calculation of components of velocities and accelerations in the plane of progression of the various parts of the body, a method using interrupted lights was employed. Small ophthalmic electric bulbs were attached to the subject at estimated joint centers of the leg, iliac crest, and heel and toe of the shoe. The lights

were illuminated continuously with a 3-volt battery carried by the subject, who walked in a darkened room and in front of the open lens of a view camera. The field of view of the camera was interrupted 30 times a second by means of a disc having an 18 degree opening, rotated by means of a synchronous motor. A Kodatron speed lamp, synchronized with the rotating disc opening, was used for obtaining a photograph of the subject in midfield for purposes of identification. The resulting record, as shown in FIGURE 3 (lines drawn later on the negative), shows the path of selected points and, with all data contained on one negative, makes possible an accurate determination of velocity and acceleration.

FIGURE 3. Interrupted light study of displacements.

Data reduction consisted of measuring the distances between consecutive dots with a toolmaker's microscope (30X), correcting for the scale factor, and dividing by the time interval of 1/30th of a second. Acceleration-time data were obtained by making a similar numerical differentiation of the velocity-time curve. Typical results for a normal subject are shown in FIGURE 4.

As a check on the accuracy of the resulting data, methods of graphical differentiation and direct recording from small electrical accelerometers were used. Both were inferior to the numerical method. Determination of the velocity and acceleration from 35-mm. moving pictures was the most rapid method used because of the ease of working from projected frames, but the accuracy was the poorest due to the relatively large light spots and the graininess of the film.

Interrupted light data alone have not proved to be very useful in the

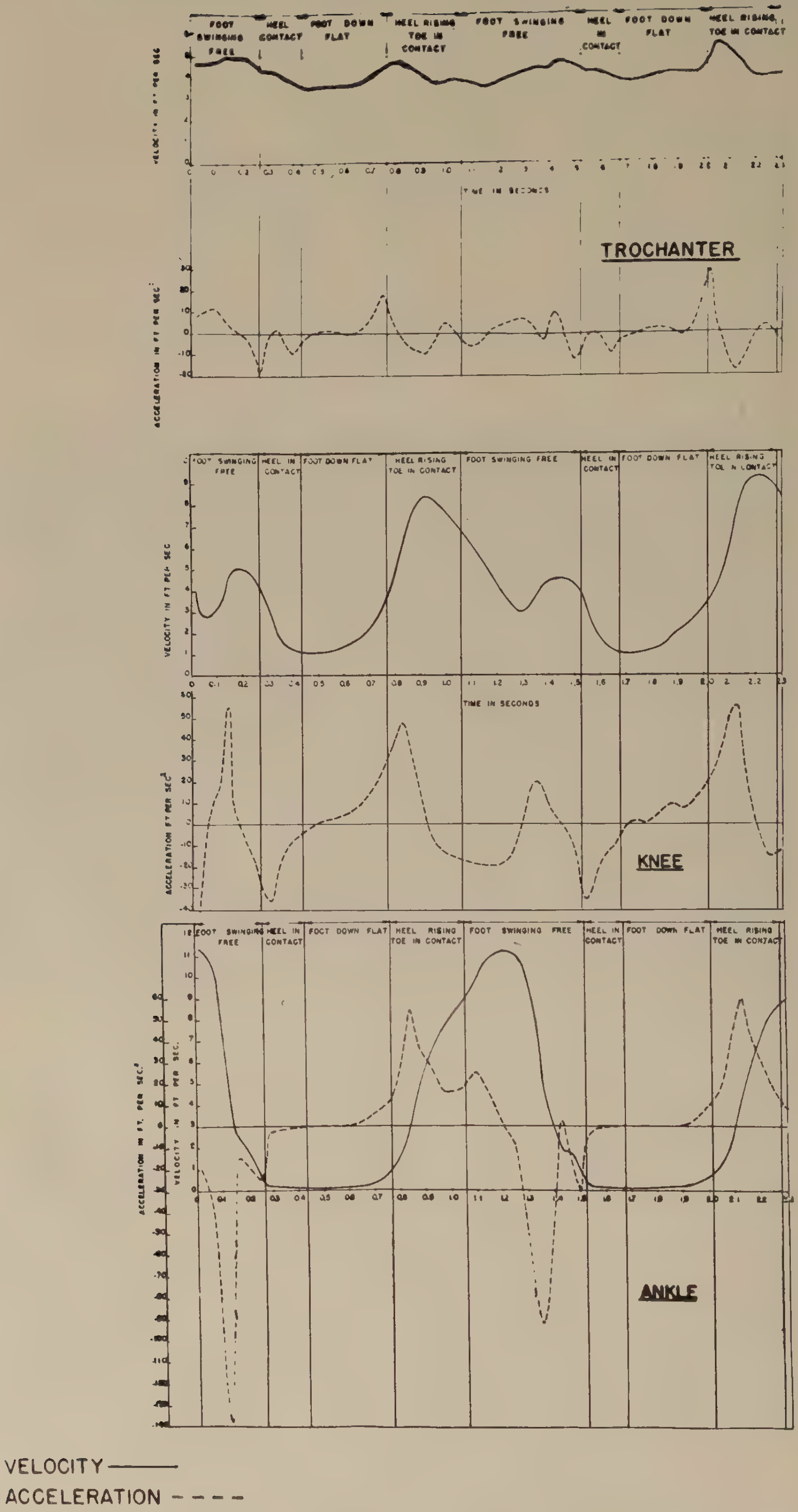

FIGURE 4. Horizontal velocity and accelerations of joints of the leg obtained from figure 3.

evaluation of gait. Their main usefulness lies in the determination of simple stick diagrams, comparison of velocity and acceleration data, and as necessary information for the determination of forces acting on the leg during the swing phase.

Pin Studies. To determine accurately the amount of transverse rotation occuring in the various segments of the leg, it was found necessary to fix targets to the pelvis, femur, and tibia. Ideally, these targets should be placed normal to the axis of rotation and should be long enough so that the end of the targets would be sufficiently displaced to reduce the errors inherent in the data reduction. To be certain that the motions recorded were those of the underlying structures, it was felt necessary that these targets be firmly affixed to bone. Therefore, stainless steel screw pins with a diameter of $2\frac{1}{2}$ millimeters were drilled into the cortices under a local anesthetic. The regions selected were the tuberosity of the ilium, the adductor tubercle of the femur, and the tibial tubercle. The selection of the adductor tubercle of the femur was necessary because of the fact that placement on the outer side so restricted movement of the iliotibial tract that motion of the knee was suppressed. Location of this pin, however, necessitated the use of a balsa wood yoke so that the target could be carried on the outer side of the leg. Targets, each consisting of a light wood rod, with spheres attached at two points, were fastened to the pins. FIGURE 5 shows a subject with pins and targets ready for the start of a test.

A photographic record of the movement of the targets was obtained by 35-millimeter synchronized motion picture cameras operating at 48 frames per second and so located as to refer the target to three mutually perpendicular coordinate reference planes, as shown in FIGURE 6. In this manner, top, front, and side views of the subject were obtained simultaneously and a clock mechanism made it possible to identify related frames which were studied from enlarged projected images. In this study, only the film from the camera, which was mounted above the subject and which recorded motions in the horizontal plane, was reduced. Records were obtained for level walking, as well as up and down ramps and stairs.

The first method employed in the reduction of the data made use of the computed space coordinates of the targets. This was felt to be necessary to correct for possible error due to perspective and parallax. Later, it was found that, in certain cases, the angle between the pins obtained from the computed projections compared favorably with the values obtained from the measurements taken directly from the photographs showing the projections upon the horizontal plane only. Analysis showed that, if the pins were set within 10 degrees of being parallel to the horizontal plane, angles between the pins could be read directly from the photographs, giving results which were within 2 degrees of the true values for the middle 60 per cent of the stance phase. The maximum variation between values obtained by the two methods occurred at the instant of toe-off, the uncorrected value being as much as 5 to 6 degrees less than the computed value. The difference between computed values and those obtained from the motion picture frames were not significant, since the variations were less than those among the

individuals tested. Phase relationships were not affected by the results obtained from the two methods.

This appears to be an adequate method of studying horizontally projected rotations which occur about the longitudinal axes of the various segments. The method of data reduction is laborious and time-consuming.

FIGURE 5. Subject with pins and targets ready for recording rotations.

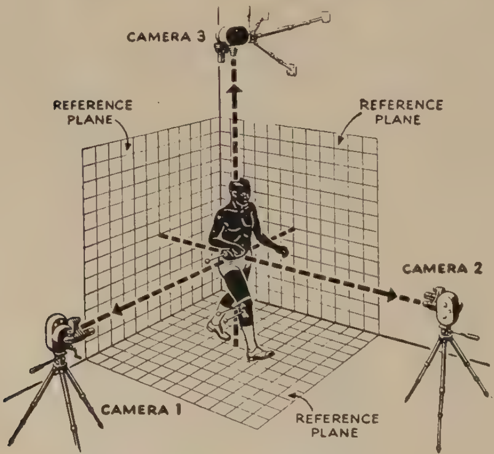

FIGURE 6. Arrangement for recording pin-study data.

The disadvantages are the personal discomfort of the subject and the possibility that some motions are suppressed due to discomfort. The latter factor is insignificant, since rotation comparison of the leg carrying pins and the subject's other leg indicates little difference.

Final data on rotations, in the horizontal plane, of the pelvis, femur, and tibia were obtained from 12 subjects selected from a total of 19 who had

three pins inserted and who walked without apparent restraint. The selection was made on the basis of parallelism of the pins to the horizontal plane and minimum pin vibration. Seven additional subjects were tried but either pins loosened, motion was restricted, or the data were otherwise incomplete. FIGURE 7 shows average curves obtained from the individual curves of 11 subjects and represents general trends only. Variation between subjects was relatively large, but the direction of rotation and the range of motion were significant.

High-Speed Moving Pictures. Fearful that certain details of locomotion might escape perception when photographed at 64 frames per second, or slower, high-speed movies were taken. In order to make the records with a greater number of frames per second, a 16-millimeter camera capable of recording 3,000 frames per second was used, but for purposes of studying

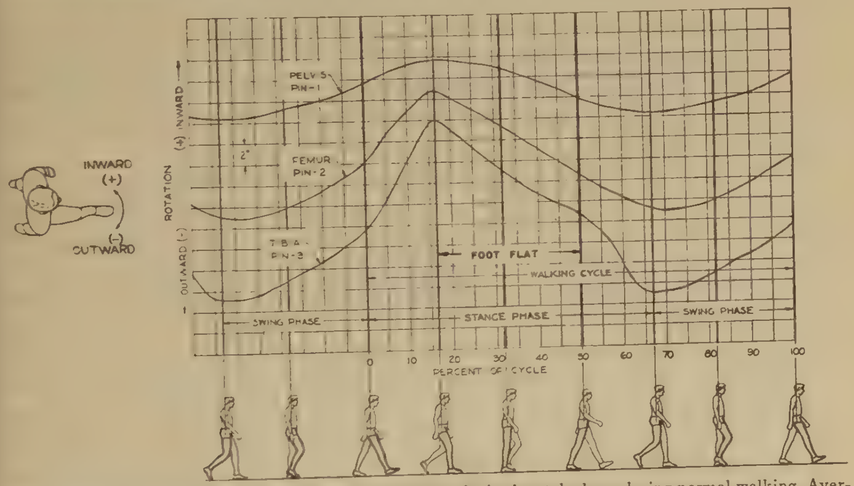

FIGURE 7. Rotation of the pelvis, femur, and tibia in the horizontal plane during normal walking. Average curves of eleven normal subjects.

locomotion it was operated at a speed of four hundred to seven hundred frames per second. Satisfactory films are difficult to obtain, and the runs must be made out of doors in the bright sunlight.

The use of high-speed moving pictures was of no advantage over the slower speeds for furnishing quantitative data on the displacement of the various portions of the body. Its only advantage was in picking up certain details of locomotion which escaped perception if photographed at lower speeds. Usually, these motions were of small magnitude and in themselves difficult to measure without the possibility of large errors. The high-speed movies were regarded as a supplement to other methods and a quantitative evaluation of certain motions. They were of more value in studying the trick motions and rapid or jerky movements which occur in amputees and those suffering from paralysis, than in the study of normal locomotion.

X-Ray Moving Pictures. For a study of pathological locomotion, particularly in those cases where braces or artificial members are used, it is desirable

to obtain accurate information regarding relative motion between the device and the skeletal structure during normal use. A detailed study of bone movement at joints of the normal leg should also prove valuable in attempting to improve the function of existing appliances.

Work with still X-ray equipment has indicated the probable value of similar data taken during walking. Equipment is now partially complete for obtaining 30 frame per second X-ray moving pictures and should be a useful supplement to previously described techniques.

Experimental Techniques—Forces

Electromyography. The displacements of the various parts of the body are produced by an interplay of gravity and muscular forces. The effects of gravity reflect in increased or decreased muscle forces and ground reactions. It is thus imperative to study muscle action in relation to locomotion.

Several methods of investigation are available for the study of muscle action during walking. These range from purely descriptive anatomy through palpation and electromyography to theoretical calculations from consideration of the motions produced during walking, such as has been reported by Dr. Elftman.

The method requiring the fewest assumptions and affording the most convenient study of muscle action is electromyography, wherein the minute changes in electrical potential of the muscle fibers accompanying contraction are recorded for examination. This method has been used in our studies for a time sufficient to indicate its limitations, as well as its advantages. Eight major muscle groups activating the leg and pelvis for each of ten subjects have been investigated, both for normal walking and to ascertain the effects of changes in cadence and going up and down stairs and inclines.

Rather than use needle or wire electrodes which produce discomfort when inserted into active muscles, surface electrodes were applied to a portion of the skin overlying the muscles. By first abrading the skin and then applying an electrode jelly, the external resistance of the contact was reduced to a value comparable to that attainable by use of wire or needle electrodes.

The action potentials were amplified by a four-channel electroencyphalograph, then recorded by a twelve-channel oscillograph in two ways simultaneously. The first was simply a record of the potentials as received from the amplifier. The second required the use of an integrator circuit which recorded only the envelope of the many potential variations, the variations themselves being stripped from the circuit by sufficient demodulation (rectification) and filtering. This produced a smooth curve which alone was used in the reduction of data, except for the determination of precise phase relationships, which required examination of the direct myographic curve. Both are shown in the typical record, FIGURE 8.

To correlate the phasic activity of the action potentials with the placement of the feet, electrical contacts were placed on each heel and toe of each subject, causing a signal to be recorded by the oscillograph on a channel separate from those occupied by the two myographic records. The large number of channels available made it possible to record the activity of two muscle groups (usually antagonists) simultaneously.

By superimposing the records of six different steps for one individual, and tracing a smooth curve through the result, individual summary curves, such as those shown in FIGURE 8, were obtained. When plotted with equal scales for maximum deflection and duration of stance for all subjects, the summary curves for each of the several individuals may be compared by simple inspection; they, in turn, may also be superimposed to obtain summary curves for a group of individuals, such as was done for the quadriceps group activities of two subjects in FIGURE 9. As is exemplified by FIGURE 9, the curves of the eight major muscle groups revealed good agreement of phase relationships among the ten subjects. One of the inaccuracies of the method is illustrated in the same figure. It is felt that the "spread" of the time of occurrence of maximum deflection exhibited in the superimposed curves of ten subjects reflects more the possibility of error in indication of time of heel strike by the

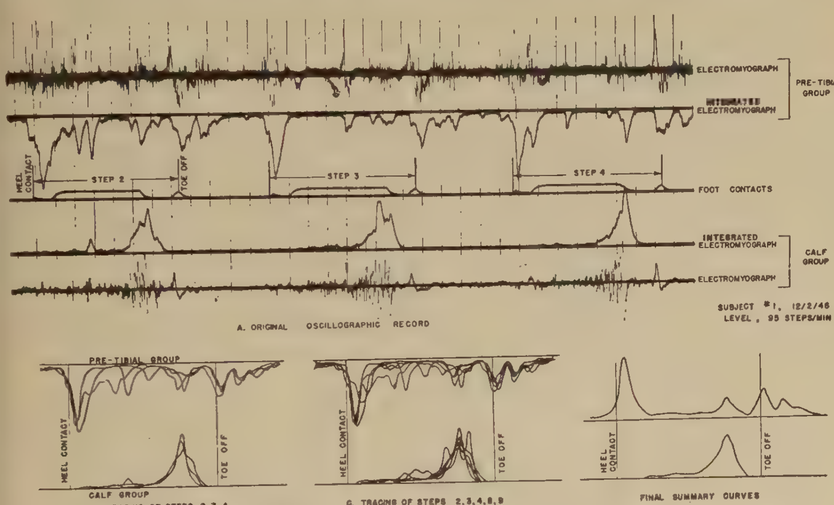

FIGURE 8. Method of electromyographic data reduction. Part 1: obtaining summary curves.

electrical contacts than it does an actual dissimilarity among individuals. It was extremely difficult to place the contacts in such a way that the signal coincided exactly with heel contact.

FIGURE 10 demonstrates the effect of different cadences and departure from level walking on the recorded activity of the quadriceps group. Such data should prove invaluable in the design, for instance, of a muscle-activated control for a prosthesis.

Although it was hoped, in the beginning, that a definitive relationship between action potential and force produced could be ascertained, such has not proved possible so far. Because of such intervening factors as variability in placement of the contacts, amplifier gain, contact resistance and so forth, only qualitative relationships were possible. Further, it was found that there is no definite relationship between the action potentials and tension even in isolated muscles subjected to length-tension tests. Only when the muscle was not permitted to shorten and there was no spatial displacement

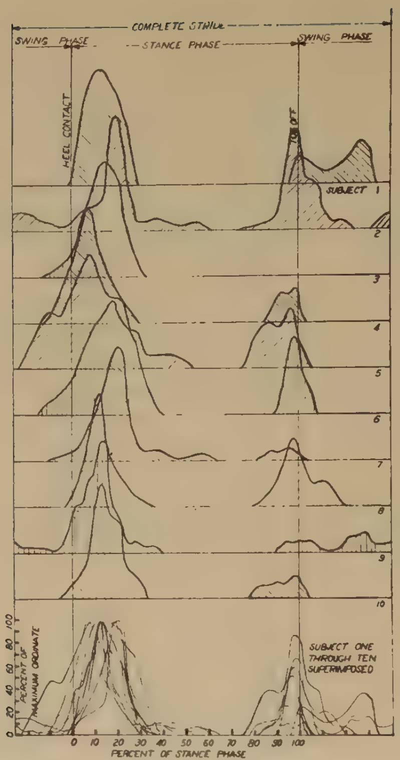

FIGURE 9. Individual variations in electromyographic summary curves for the quadriceps group of ten subjects. Cadence: 95 steps/min., level walking.

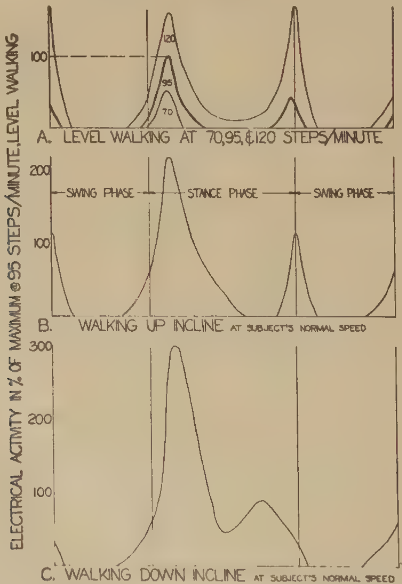

FIGURE 10. Composite curves showing phase relationship and magnitudes of electrical activity as affected by change of walking condition—quadriceps group.

of electrodes, was such a relationship evidenced. It is reasonable to deduce, then, that for limited movements an increase in potential indicates a rise in tension. No such limitations, however, need be stated in regard to the accuracy of the phasic connotation of the electromyographic records.

Force Plate Studies. As a means of direct measurement of all ground reactions, including torque, the force plate used in the present studies is sufficiently adequate. Experience has shown its discrete advantages and limitations. It records the magnitudes of vertical force, torque, and horizontal shears as well as the center of pressure on the foot (the location of the resultant vertical force). While it does not define the lines of action of the fore and aft and the lateral shears, it does record the resultant effects of their location by combining them with the applied torque and indicating an equivalent horizontal force and moment system at the center of the plate. To determine the actual distribution of pressure on the foot, however, recourse was had to experimentation with a barograph similar to that developed by Dr. Elftman.

The absence of any movement of the plate (except for infinitesimal deformations of the supports which serve to measure the reactions) is conducive to faithful simulation of actual walking conditions, at the same time providing a convenient means of permanently recording the reactions produced. Essentially, the plate on which the subject steps in the course of a short walking exercise is rigidly attached to four columns, the deformations of which are measured by electrical strain gauge bonded thereon. A twelve-channel Heiland oscillograph is used to record these deformations. Amplification is required in the circuits used for vertical load and the x and y coordinates of its line of action. By applying known loads to the plate, the tape deflections can be easily calibrated and results examined. Recourse to FIGURE 11 will help demonstrate the simplicity of the equipment.

The force records are synchronized to the location of the subject by two means: motion pictures of the entire scene, including a timing device, and placement of a piece of carbon-backed paper on the plate to record the position of the foot with respect to the center of the plate. The latter was necessary since the plate records a system of reactions and location of center of pressure referred only to the center of the plate.

From these data, the results may be plotted in the way shown in FIGURE 12, in which it must be noted that the torque shown is computed with respect to the location of the ankle target (see FIGURE 11, top), since only then will it have a concrete significance.

In considering the body as a whole, knowledge of the total body weight in addition to the measured ground reactions is all that is required to determine the behavior of the center of gravity of the body. Simple mathematical treatment by integration of the resultant of these two forces enables the calculation of the translational velocities and displacements (but not the absolute position in space) of the center of gravity of the body as a whole.

The computation of resisting force systems within the body, however, requires the utilization of motion pictures and specialized computation techniques, the limitations of which have been indicated.

FIGURE 11. Top, force plates being used. Bottom, details of U. S. force plate.

The sources of error in the force plate studies may be classified in two ways: errors in recording rapidly applied loads, and those in recording the more gradually applied loads.

The frequency response characteristics of the galvanometers used affect the recording of both types of loading, but, for the suddenly applied loads, the largest source of error is in the relatively large mass of the top plate. It

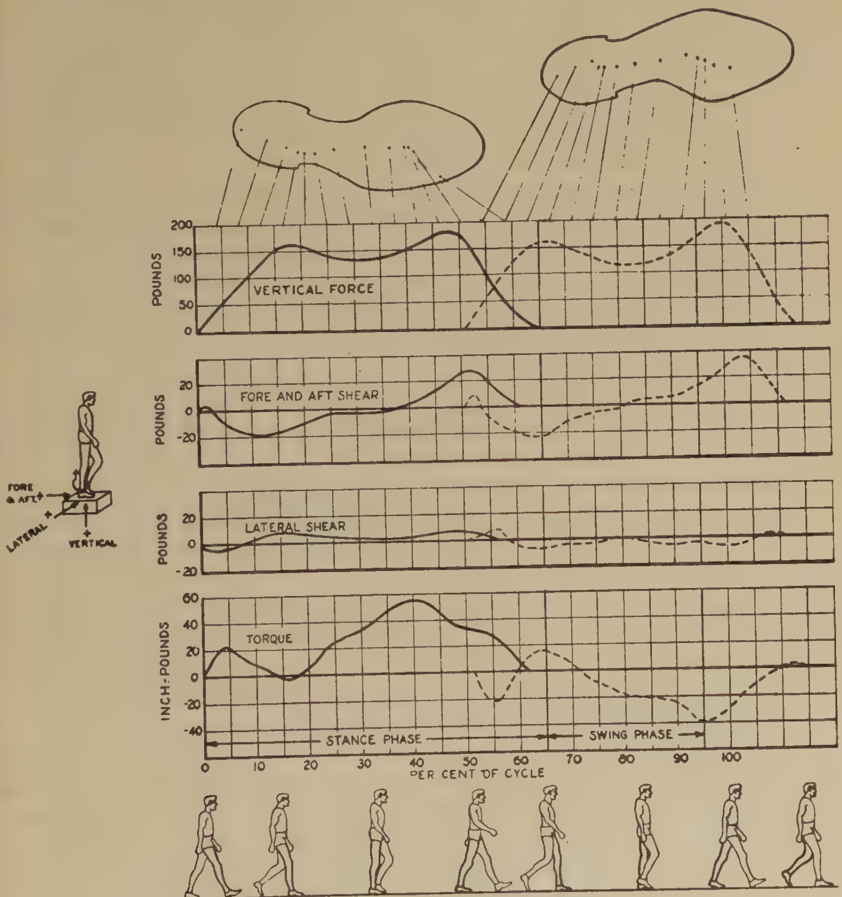

FIGURE 12. Typical force plate results for a normal subject during level walking.

is felt that the inertia of this plate precludes a complete transmission of load to the measuring columns. This effect may have caused inaccuracies in measuring impact loads as great as 50 per cent of the true value. For the more gradually applied loads, however, only the response of the galvanometer need be considered. Calibrations have shown that the recorded values of peak loads (where rate of change of load is a minimum) probably are not in error more than 2 to 4 per cent, depending on the degree of amplification required.

A significant limitation to the use of the force plate, however, is that only those reactions occurring during the stance phase of walking can be recorded. In order to complete the cycle and include the swing phase, the pylon was developed for use with amputees.

Pylon Studies. By replacing the shank portion of an artificial limb with a tube on which electrical strain gauges are bonded, studies were made of the forces acting on the shank at all times. Thus, for amputees at least, the prime limitation of the force plate is removed. The strain gauges, electronic equipment, and instrumentation are identical with that used with the force plate, and the same high degree of accuracy as was obtained for peak loads on the force plate (the inertia of the pylon tube is negligible) was achieved. The notable exception is the torque recording circuit, which could deviate as much as 12 per cent from true torques.

By having the pylon-equipped amputee step on the force plate, direct comparisons were made of the two load-measuring systems. Such comparisons have shown very close agreement of the two systems.

Experience gained in many pylon studies has revealed some additional advantages in the method. The system is very sensitive to certain changes in the prosthesis, such as alignment, bumper stiffness, and other details of adjustment. Thus, this instrument is of particular help in improving artificial limbs and broadening the knowledge of researchers in pathological gait, as well as in filling out, even if only quantitatively, our knowledge of the forces called in to play during the swing phase of normal locomotion.

Internal Resisting Forces and Moments. The calculation of the force systems acting at the joints within the body combines the data obtained from the force plate and the glass walkway, and therefore must contain whatever errors are inherent in those methods.

The data were combined by the use of Newton's laws of motion and required the assumption of such physical constants as the location of centers of gravity, the relative masses, and the principal moments of inertia of the various segments of the leg. Therein lies the principal limitation of the method.

Of the various means of estimating the values of these constants, Fischer's coefficients seemed to be the most convenient. Experimentation is now in progress by which it is hoped that these coefficients may be checked, at least for certain particular cases. At best, these may serve only as means of comparing the internal force systems for subjects of similar build.

Summary

The use of modern photographic and electronic techniques with attention to the proper control of variables has made possible the collection of data of sufficient accuracy to indicate the principal details of behavior of the lower extremity and pelvis during locomotion. The integration and synthesis of these data should contribute to a better understanding and utilization of corrective procedures for the improvement of cases of pathological locomotion.

SOME RECENT DEVELOPMENTS IN LOWER EXTREMITY PROSTHESES

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Research and experimental work leading to the improvements referred to in this paper was sponsored by the Advisory Committee on Artificial Limbs as advisors to the Veterans Administration, the Surgeon General's Office, and the National Academy of Sciences. The paper describes recent developments in lower extremity prostheses, and the design application of fundamental research data by Elftman[1–15] and the University of California.[16]

Although the comfort of the amputee is of paramount importance, this paper is not intended to cover the alignment and fitting techniques, or the method of application to the body such as the suction socket invented by Parmelee in 1863,[17] both of which are under investigation at the University of California. Rather, the intent is to discuss the basic functional requirements of lower extremity prostheses, the nature and significance of the more important functional characteristics required, and to describe their incorporation in leg design.

A review of prior art by Northwestern[18] and a study of standard English[19, 20, 21] and German[22, 23, 24] works reveal in great detail the structure, operation, and problems in the design of prostheses, such as outlined by Murphy.[25] In prior work, however, practical leg designs incorporating the desirable functional requirements were not fully developed.

An examination of the University of California functional data on relative rotation (FIGURE 1) would indicate that, if a prosthesis could be designed having the following sequence of operations, the normal walking gait would be very closely duplicated.

Stance Phase. Directly following heel contact of the prosthesis, plantar flexion in the order of 15° to 20° occurs. Provision should be made for gradual deceleration and shock absorption for resisting the torque about the ankle as a result of the vertical force shown by Eberhardt and Inman,* and permit angular velocity similar to the tarsal-tibia curve (FIGURE 1). Concurrent with ankle extension following heel contact, weight bearing initial knee flexion should occur within a range of 12° to 15°. Directly following maximum initial knee flexion, both the knee and ankle should return to normal position at a uniform rate as the center of gravity moves forward, the return to normal position occurring when the center of gravity is directly over the ankle or at the point of full axial load. Between full axial load and heel contact of the normal leg, it is most important to consider provisions for shock absorption at the ankle joint and to store a portion of the kinetic energy of the body during dorsiflexion of the ankle, which would later be returned during the push-off phase. This shock-absorbing medium should provide for maximum dorsiflexion during heel contact of the normal foot in the order of 12° to 15°. Immediately preceding heel contact of the normal

* See FIGURE 12 p. 1227.

foot, weight bearing controlled knee flexion of the prosthesis should occur with sufficient resistance to torque about the knee within a range of approximately 5° just prior to heel contact of the normal foot.

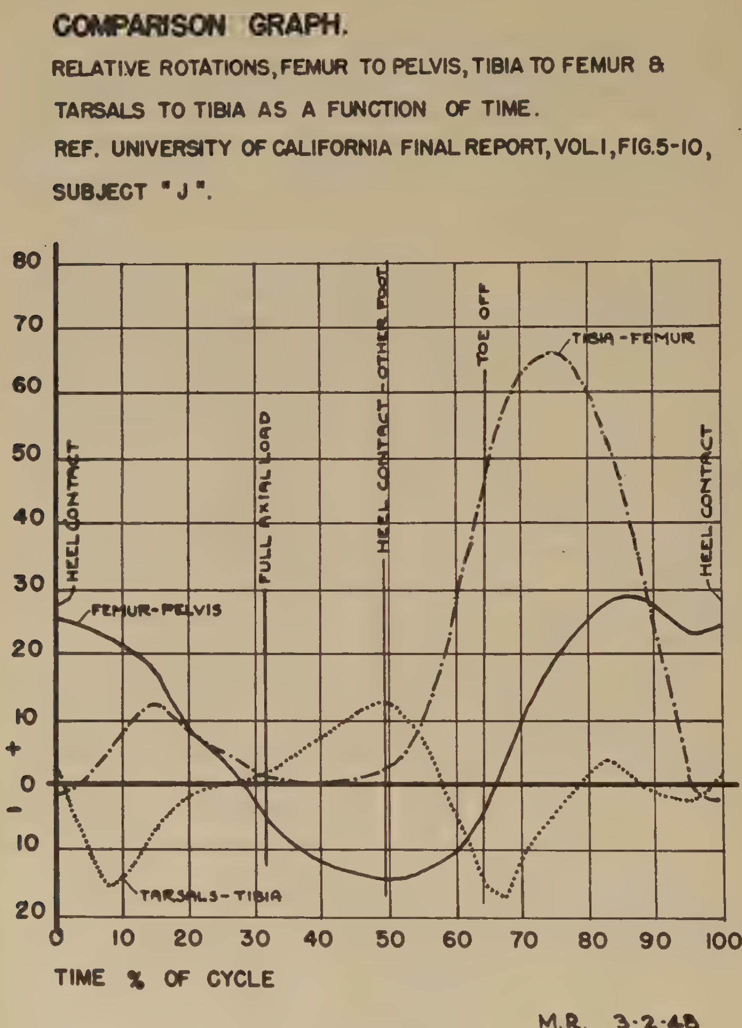


Figure 1.

Swing Phase. Directly following heel contact with the normal foot and as the weight shifts from the prosthesis to the normal leg, the mechanism controlling resistance to torque about the knee should release in such a manner as to provide for uniform and rapid knee flexion. Directly following heel contact of the normal foot and as knee flexion occurs during the start of the swing phase, ankle extension should follow with maximum ankle extension occurring directly after toe-off of the prosthesis. The ideal degree

of ankle extension during the push-off phase would be between 30° and 35° from the position of maximum dorsiflexion upon heel contact of the normal foot. Directly following maximum knee flexion and maximum ankle extension during the swing phase, knee extension and ankle flexion occurs.

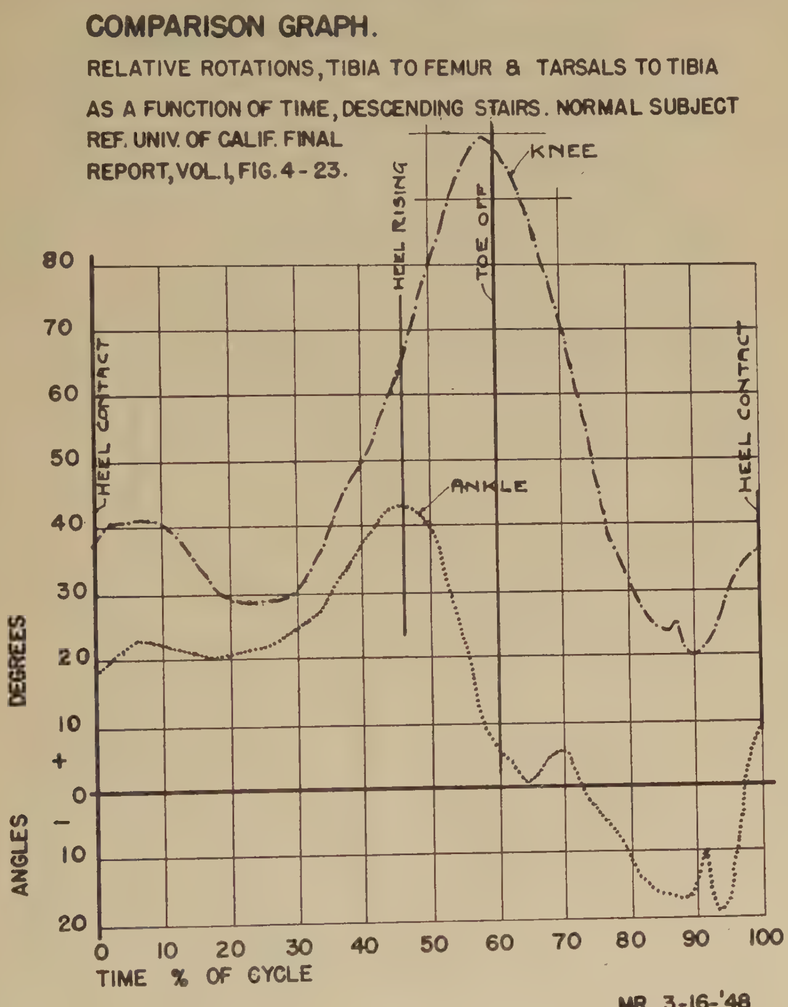
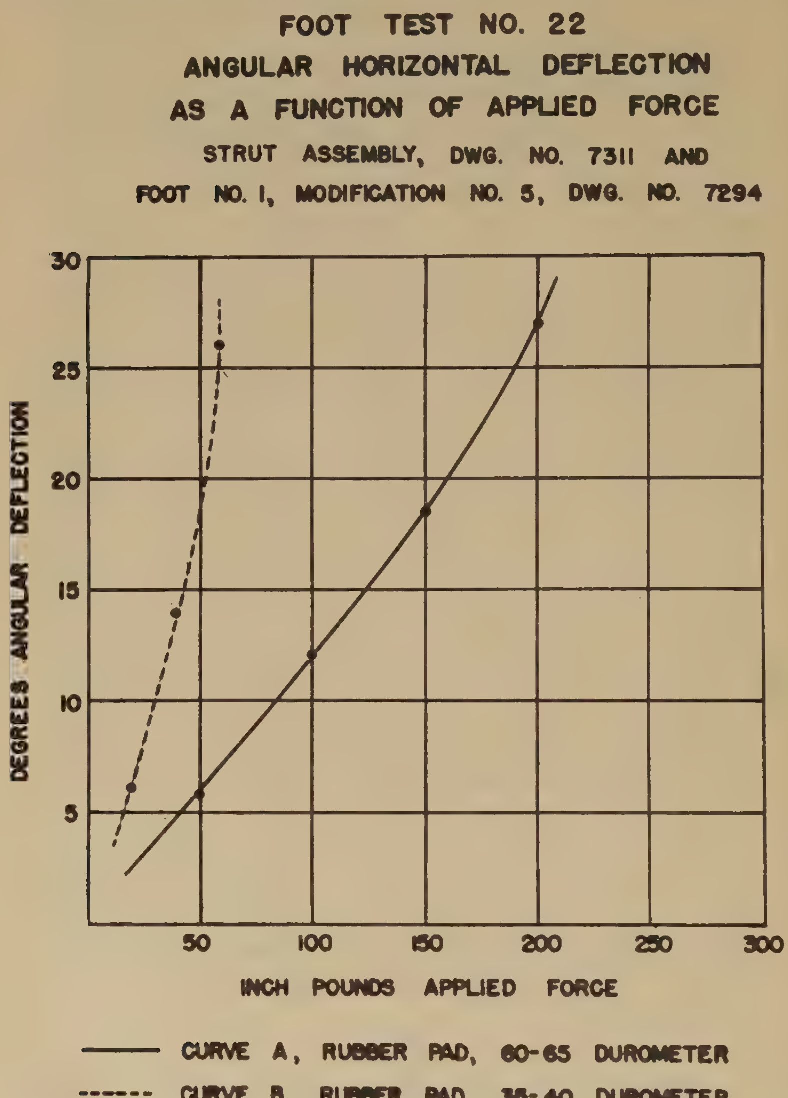


FIGURE 2.

Provision should be made for deceleration of the prosthesis so that, upon return to the normal, shock is eliminated upon full extension of the knee. Such provision for decelerating the prosthesis should take into consideration arrangements for change in cadence and the resultant shock-absorbing requirements. During the latter part of the swing phase, approximately 5° of dorsiflexion from the normal datum is required for clearance between the

walking surface and foot, or a total of slightly more than 20° from the position of maximum ankle extension directly following toe-off of the prosthesis. The limits for dorsiflexion and knee flexion incorporated in the design of the



[Figure 3.

prosthesis must take into consideration the greater values for flexion when descending stairs (see FIGURE 2). It will be noted that a maximum of 45° dorsiflexion of the ankle and 100° knee flexion occurs during this service.

In addition to flexion and extension of the knee and ankle joints, rotation of the body about its center of gravity occurs as it moves forward. Investi-

gations by Elftman, and the University of California, would indicate that provisions in the prosthesis for rotation about the vertical axis, would minimize the shear effect between the stump tissues and the femur.

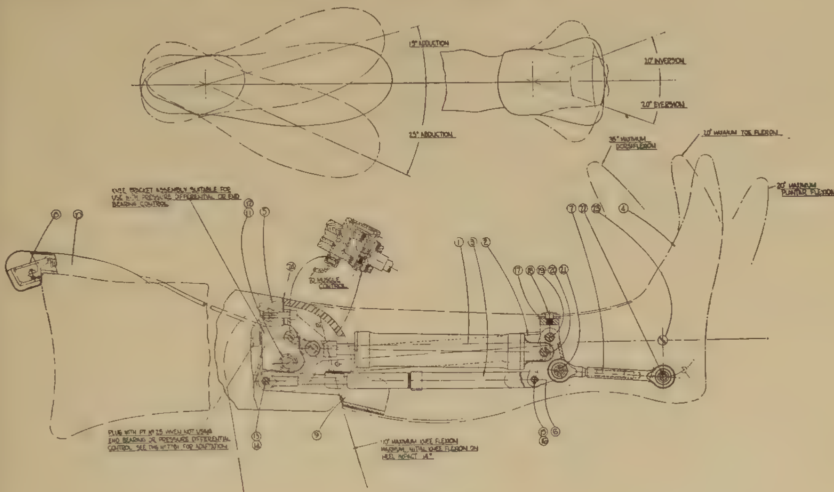


FIGURE 4.

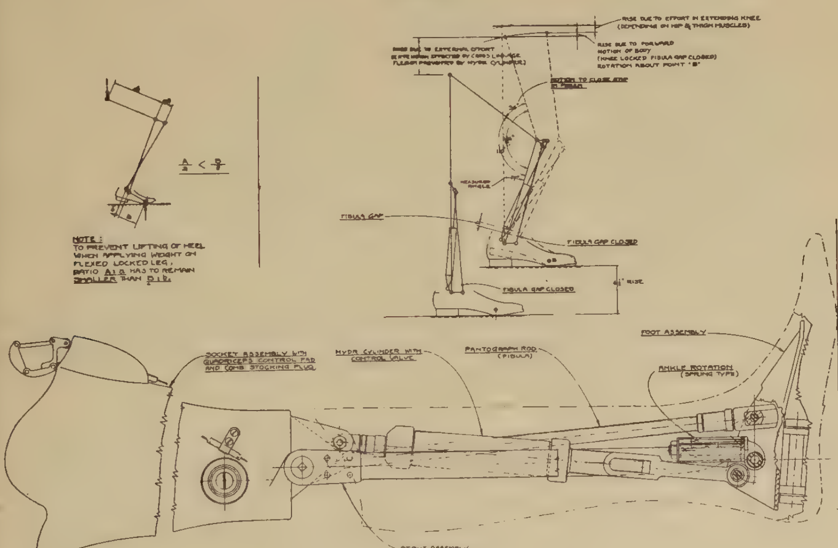


FIGURE 5.

Eberhardt and Inman's FIGURE 12* indicates the torque about the ankle, and FIGURE 3, the result of design application of the fundamental data on a prosthesis providing for horizontal rotation in accordance with FIGURES 4 and 5. This consideration for horizontal rotation is especially important when applying the prosthesis by means of a suction socket, inasmuch as the

* See p. 1227.

basis of application does not provide for any movement between the surface tissues of the stump and the surface of the socket.

It may be seen from the above descriptive analysis of the mechanics of walking that it is desirable to include the following functional requirements in a leg prosthesis:

(1) Freedom of motion within the limits of flexion, extension, and rotation of the normal leg.

(2) Control of knee for weight bearing.

(a) A knee capable of bearing body weight in any flexed position.

(b) Control for involuntarily locking the knee on heel impact and unlocking directly following the push off phase.

(c) Control for varying resistance to torque about the knee so as to permit descending ramp, stairs, *etc.*

(d) Voluntary override of the control so as to provide full lock when desired.

(3) Toe pickup and coordinated foot, ankle, and knee motion.

(a) Provision for toe pickup or dorsiflexing the ankle during the oscillating phase to provide clearance between the foot and walking surface.

(b) Coordinated knee and ankle flexion providing for weight bearing on the total plantar surface, ascending or descending inclines or descending stairs.

(c) Initial knee flexion upon heel contact and interrelated motion between the ankle and knee during the stance phase for knee extension.

(d) Provision for ankle extension during the push-off phase.

(4) Simulate normal ankle functions.

(a) Provisions for rotation about the vertical axis.

(b) Limited lateral motion.

(c) Plantar and dorsiflexion within normal limits.

(d) Provisions for shock absorption on heel impact and during load phase.

Many ingenious prostheses have been designed providing for angular limits of operation closely approaching the normal leg. In order to simulate the normal leg in other than fully extended knee positions, however, provisions must be made for control of the knee for weight bearing. Further, the control must be in phase with the normal gait and service requirements.

The most direct approach to the problem of control would be to utilize the phasic action of the muscle groups in the normal leg (see FIGURE 6). To accomplish control as it occurs in the normal leg, such control must be provided for involuntarily, and, as in the normal leg, this involuntary control must be overridden when and as desired by the subject. Because of the design of the suction socket, the glutei and quadriceps muscle groups were selected to provide such control.

Accordingly, a control device (Catranis[26]) was designed, utilizing the tensing of the muscles and a change in the relative position of the socket with respect to the stump when tensing the muscles or when tilting the hip, providing a control for either a mechanical or hydraulic knee lock.

The device consists of a pad or button operated either through a series of levers, or by means of a cable connected to the control medium by mechanical means, or a bellows or hydraulic chamber operating the control by means of a hydraulic medium. FIGURE 7 illustrates the relative positions during the normal walk, and FIGURE 8 the position of the control activator.

The activator is situated at the upper margin of the prosthesis, slightly lateral or outside the midline. Anatomically, this location on the stump is just distal and medial to the anterior superior iliac spine. The femoral nerve lies just medial, and, inasmuch as the femoral artery and vein are medial to the nerve, these structures are safely remote. The great saphenous vein dips down through the *fossa ovalis* directly medial to the lever and is also situated sufficiently distant (Severance[26]).

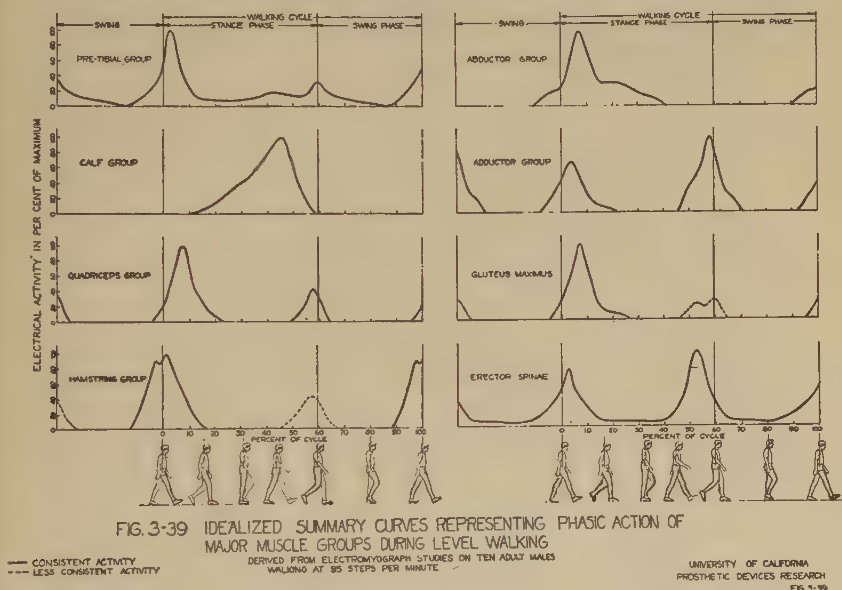


FIGURE 6.

When descending a ramp or stairs, or during a fall, the operation is as follows:

Assuming that the prosthesis is initially flexed at the knee, the axis of the femur being in its normal position with the longitudinal axis of the socket at the start of a fall or when descending a stair (see FIGURE 9, Phase A), the natural reaction is to tense the gluteus maximus and quadriceps muscle groups, among others, thereby causing the leg or stump to extend about the hip forcing the distal end of the stump against the posterior of the socket per Phase B. This causes a change in the relative position between the socket and stump, the resultant motion at the top anterior position of the socket being towards the body, the body at the hip joint at the same time pressing towards the front of the socket at the upper portion. A force is

thereby exerted upon the control activator operating either the control medium of a mechanical or hydraulic device resisting torque about the knee.

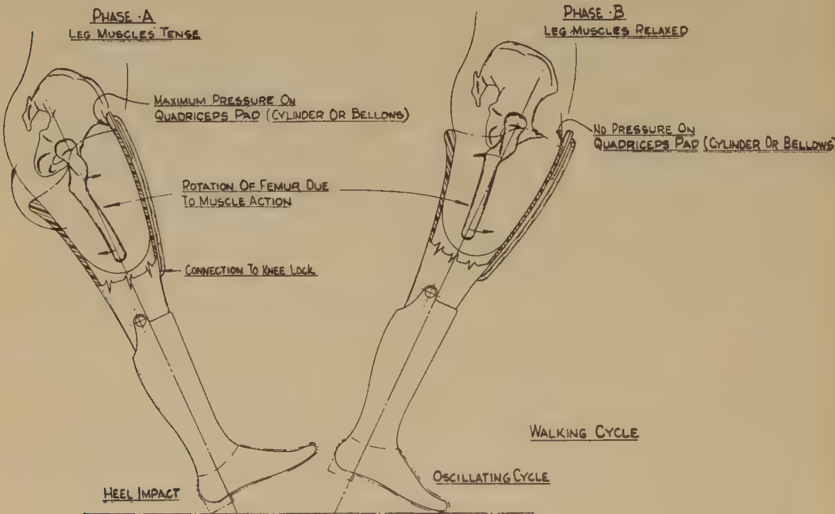


FIGURE 7.

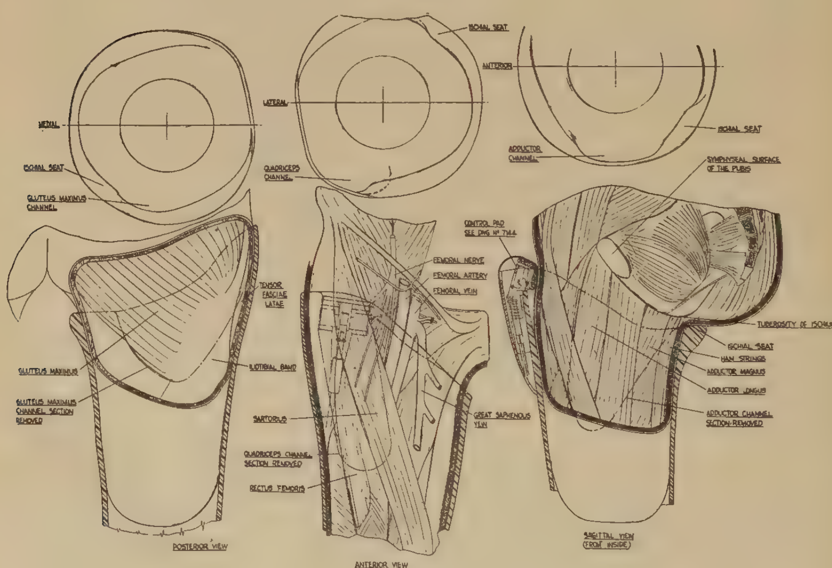
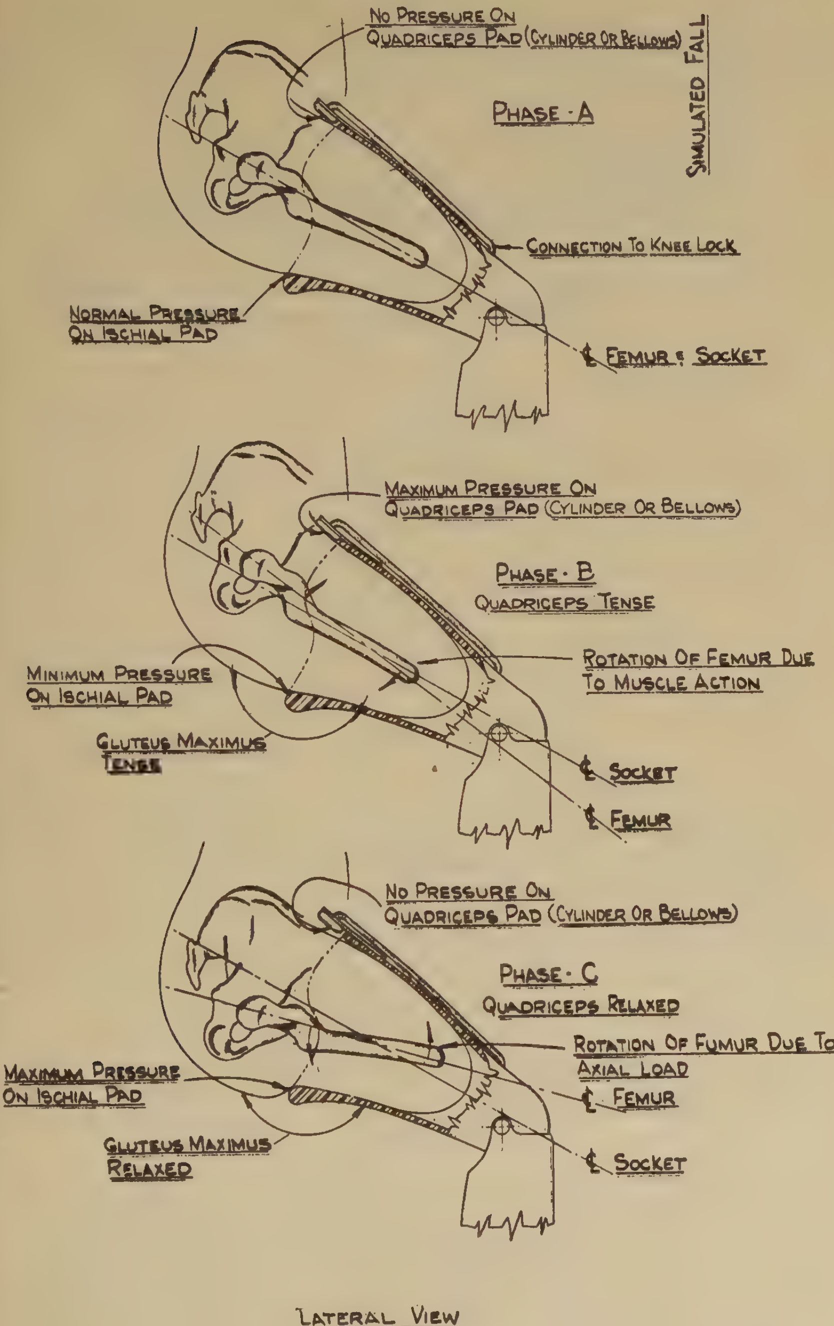


FIGURE 8.

This action is involuntary and independent of wilful action by the amputee due to the automatic action of these muscle groups for meeting normal service requirements.

As resistance to torque about the knee increases, a change in the relative



No Pressure On Quadriceps Pad (Cylinder Or Bellows)
Simulated Fall
Phase - A
Connection To Knee Lock
Normal Pressure On Ischial Pad
℄ Femur & Socket
Maximum Pressure On Quadriceps Pad (Cylinder Or Bellows)
Phase - B
Quadriceps Tense
Rotation Of Femur Due To Muscle Action
Minimum Pressure On Ischial Pad
Gluteus Maximus Tense
℄ Socket
℄ Femur
No Pressure On Quadriceps Pad (Cylinder Or Bellows)
Phase - C
Quadriceps Relaxed
Rotation Of Fumur Due To Axial Load
Maximum Pressure On Ischial Pad
℄ Femur
Gluteus Maximus Relaxed
℄ Socket
Lateral View

Figure 9.

position between socket and femur occurs, similar to Phase C. The position shown is for the full weight of the body on the ischial seat of the socket and muscles relaxed directly following initial tension. In this position, no force is exerted upon the pad. The valve mechanism, however, is designed

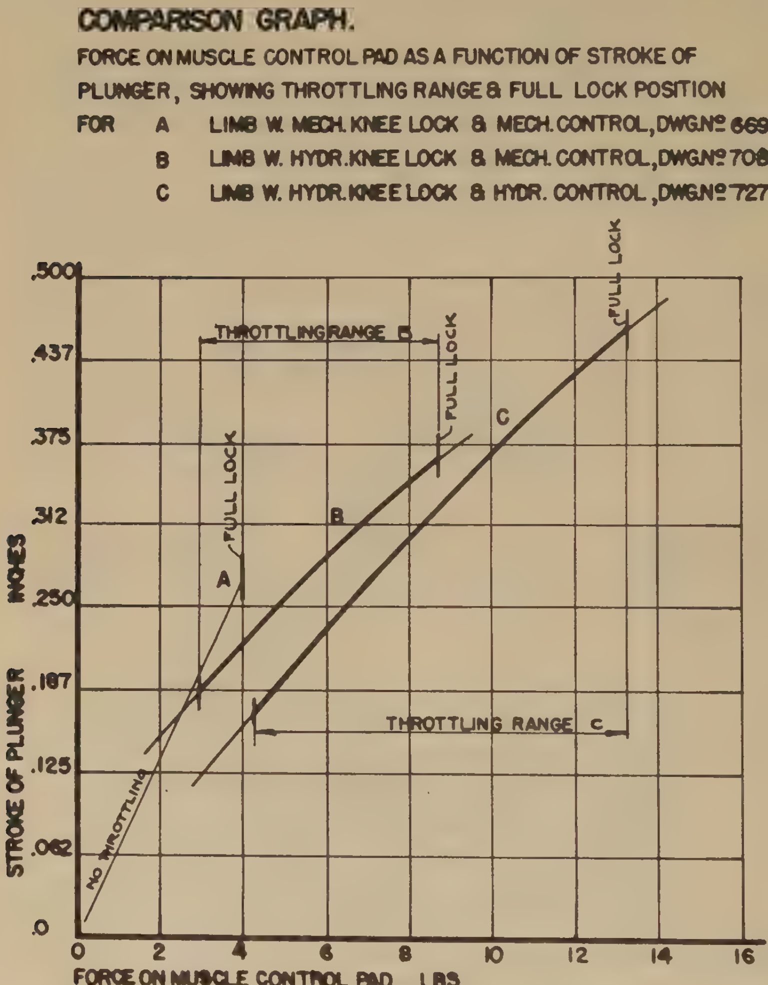


FIGURE 1.

in such a manner as to maintain a throttling position as long as there is any weight on the prosthesis.

In this position, minimum throttling action occurs but may be increased by voluntarily tensing the muscles or tilting the hip. Upon removing the weight from the prosthesis, the control medium providing resistance to torque about the knee immediately releases, permitting free flexion or extension, whichever may be required.

Force on the muscle control activator as a function of stroke of the plunger is shown on FIGURE 10. The change in relative positions between the stump and socket provide forces between 3 lb. and 13 lb. and a stroke of approximately $\frac{7}{16}''$ for the control medium.

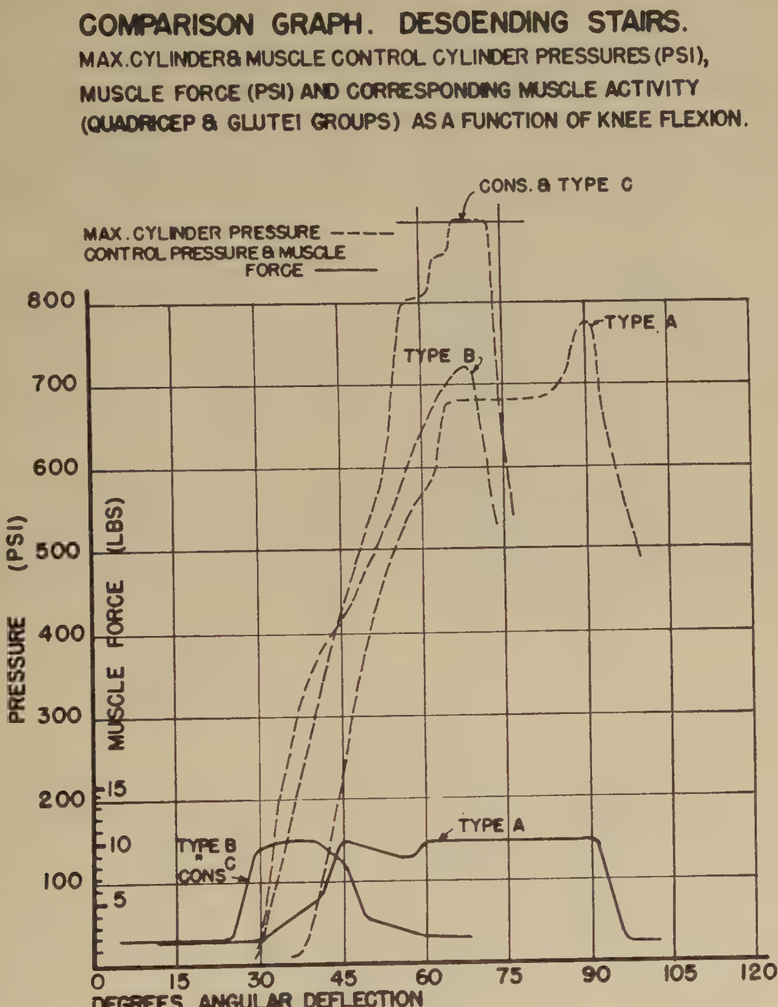


FIGURE 11.

Numerous tests were conducted with this type of control activator used on a hydraulic type prosthesis, as in FIGURE 5. FIGURE 11 is a compilation of these tests, indicating the maximum hydraulic cylinder pressures providing for resistance to torque about the knee about a lever arm of $1\frac{1}{2}''$ long, the subject weighing 147 lb., carrying 100 lb. while descending stairs. The solid line curves indicate the control phase, pressure, and muscle force.

The dotted line curves indicate the pressure in the hydraulic cylinder resisting torque about the knee.

FIGURE 12 illustrates a cross section of a hydraulic cylinder. Its principal feature is an unbalanced valve for maintaining a throttling position as long as weight is on the prosthesis. Upon application of excessive weight, further throttling action occurs due to the design of the throttling mechanism. A floating make-up piston compensates for the volumetric displacement of the piston stem and also acts as an accumulator, compensating for temperature differentials. Incorporated in the design is a means of adjusting initial resistance to torque about the knee providing for deceleration of the prosthesis during the swing phase. This is accomplished by restricting the inlet orifice at the piston by rotating lug A on the piston sleeve.

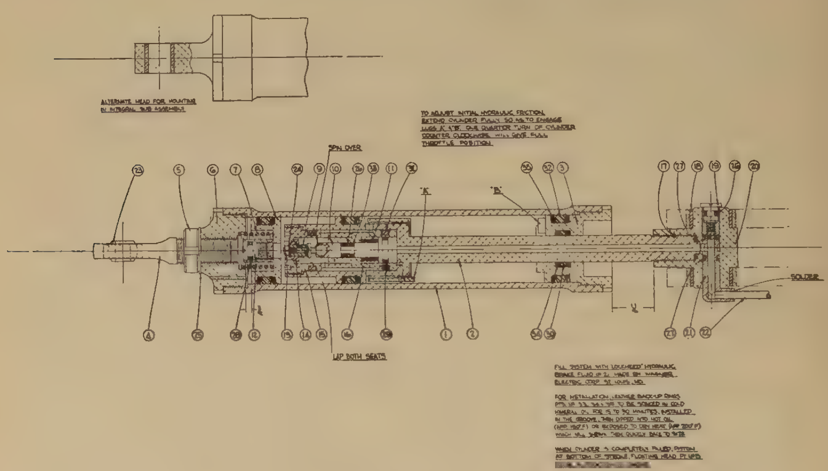


FIGURE 12.

For illustrations of an amputee descending stairs and ladder, see FIGURE 13. The prosthesis referred to as a consolidated leg in these figures is identical with the one providing curves marked "Cons." on FIGURE 11, and curve marked "C" on FIGURE 10.

Although the design of this type of control is not in final form, tests conducted on at least ten subjects wearing hydraulic prosthesis indicate satisfactory operation for normal walking, descending stairs, ascending and descending inclines, sitting down, and other functions such as stepping off a curb and full lock for recovery from fall.

Where the application of the control activator may be contra-indicated for physiological or other reasons, FIGURE 14 illustrates variations in control media wherein the distal end of the stump is used to activate the control device as a result of the change in relative position in the longitudinal axis between the socket and the bottom of the stump during normal service by means of an end bearing control, or wherein the control is activated by the pressure differential that occurs in the suction socket during normal service (See FIGURE 21).

FIGURE 13. Top, locomotion study, descending stairs. Bottom, locomotion study, descending ladder. Subject: Capozza consolidated leg.

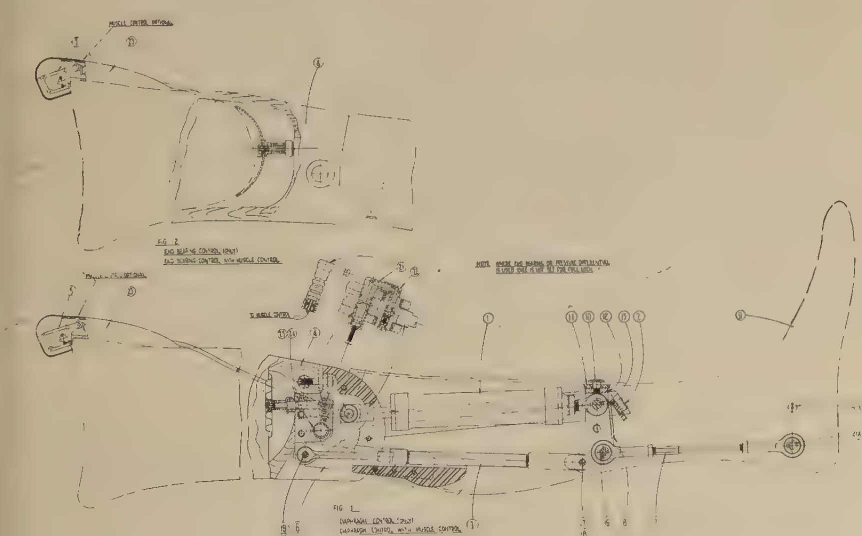


FIGURE 14.

Figure 15 indicates an alternate form of control for application where either muscle, end bearing, or pressure differential controls may be contra-indicated, the control mechanism being activated by the change in position of a metatarsal link on the foot when either ankle or foot are extended or flexed from the normal position.

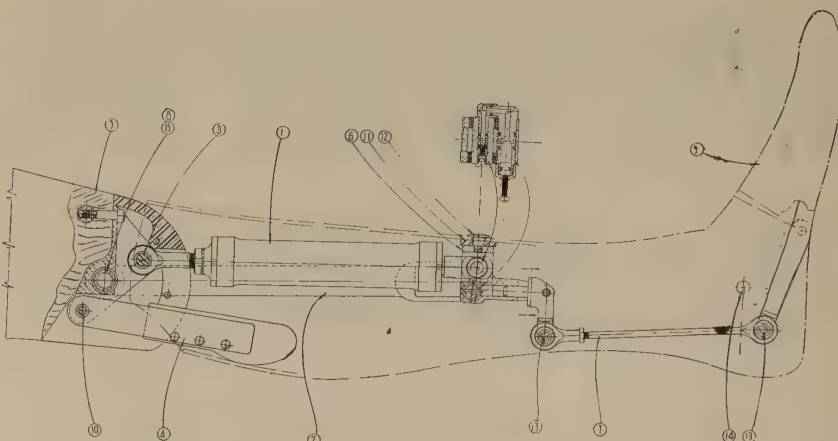


Figure 15.

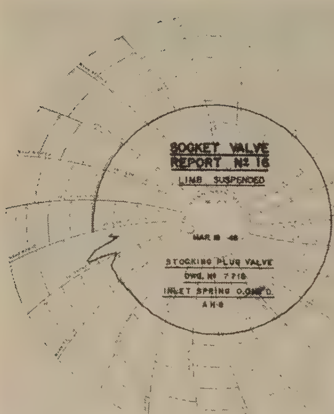


Figure 16.

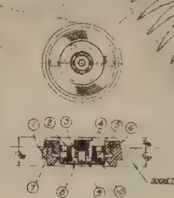


Figure 17.

Figure 18.

Although investigations of the suction socket for attaching the prosthesis to the body were primarily conducted at the University of California, experiments with pressure differential type of controls led to the development of a suction socket valve maintaining limited negative and positive pressures in the suction socket.

The principal reason for restricting the negative pressure is to minimize

the possibility of an edematous condition, and further to provide an exchange of air at each cycle by maintaining a low positive pressure. In this manner, a slight amount of air is expelled during heel contact and air taken into the socket when the effect to increase the negative pressure above an established predetermined value of 2 psi occurs. FIGURE 18 shows the pressure differentials occurring in the suction socket during the normal walk. FIGURE 16 shows the positive and negative pressures in the socket during heel impact and with the leg suspended, and the decrease in negative pres-

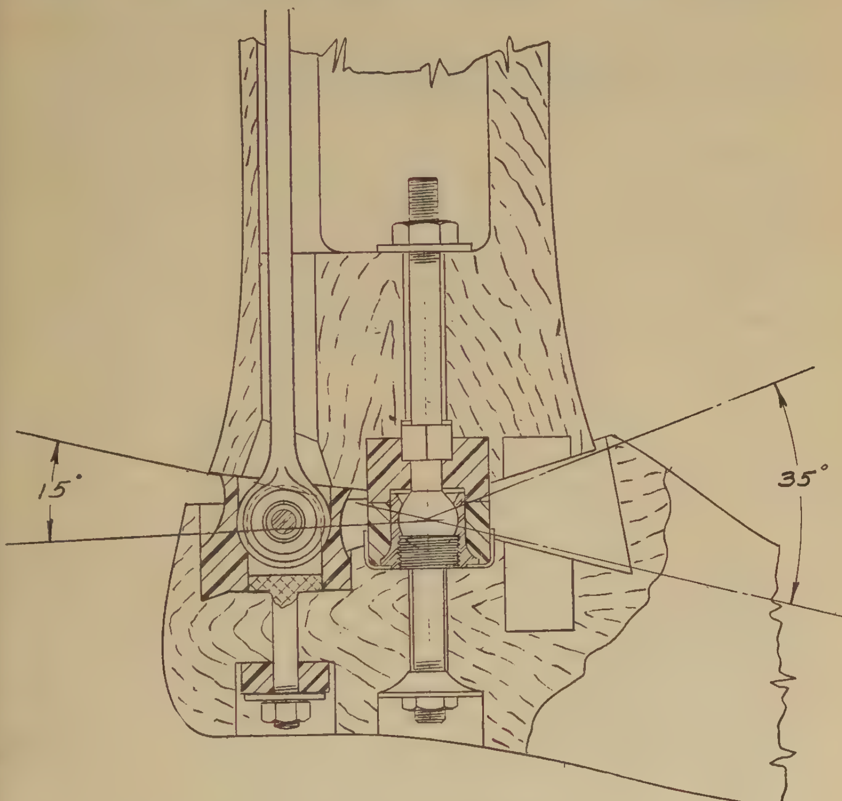


FIGURE 19. Mare Island.

sure which occurs when the leg is suspended for one full minute, muscles relaxed. A cross-section of the valve (FIGURE 17) illustrates its construction and position in the suction socket wall.

Observations made during tests on the various types of prostheses providing for controlled knee flexion indicated that provisions for coordinated knee and ankle motion greatly improved the comfort of the amputee and the appearance of his gait, especially when descending stairs, ladder, and descending or ascending inclines.

A pantograph linkage having a ratio of two to one between the knee and ankle has been included, the upper portion of the linkage, detail 3, FIGURE

4, being a hydraulic dashpot. The resistance to fluid flow limits vertical displacement of 15 pounds to $1\frac{1}{2}$ inches in 5 seconds and is sufficient to overcome the piston drag on the main cylinder and friction about other me-

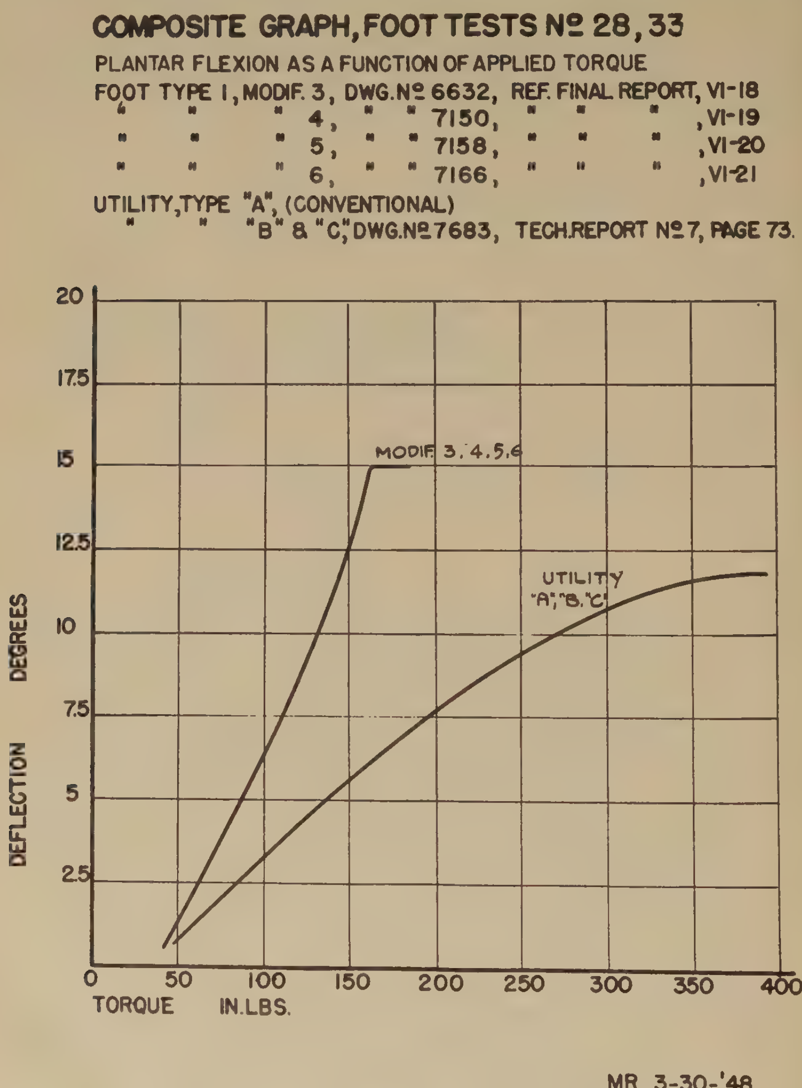


FIGURE 20.

chanical joints and the ankle joint so that dorsiflexion occurs during the swing phase, as the knee is flexed. Due to resistance about the ankle, approximately 5° of dorsiflexion occurs during normal walk. However, the force on the ball of the foot when descending or ascending inclines or when descending stairs, is sufficient to overcome the friction about the ankle, the

pantograph linkage permitting dorsiflexion of approximately 35° when knee flexion of 110° occurs. In the normal leg, initial knee flexion occurs due to the involuntary muscle action and the general design of the anatomical

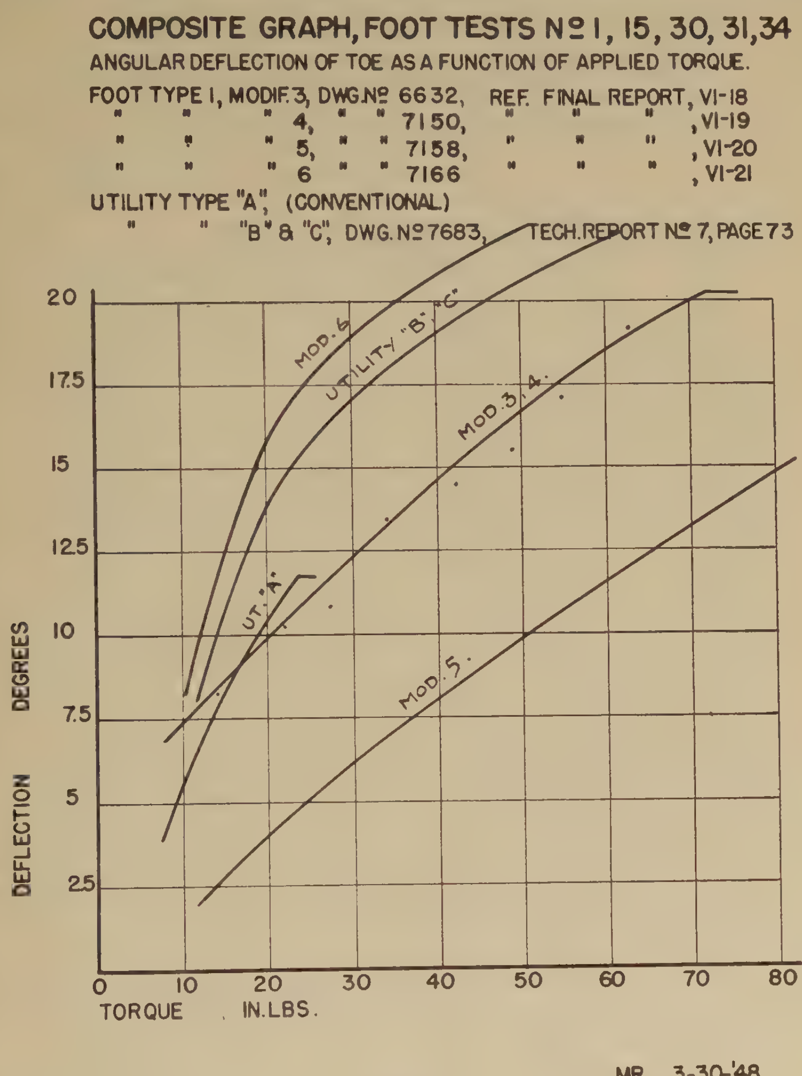


FIGURE 21.

structures. In a prosthesis, however, where it is desirable to maintain a mechanically stable position where the knee axis is posterior to the longitudinal load axis, a device is desirable to provide initial knee flexion, assuming that the mechanism resisting torque about the knee is fully locked to extend the knee and provide for full extension when the center of gravity is directly over the ankle during the load phase.

A linkage device providing for full extension has been suggested by Schede-Habermann, wherein interrelated motion between the knee and hip is utilized. The application of this principle defeats some of the advantages

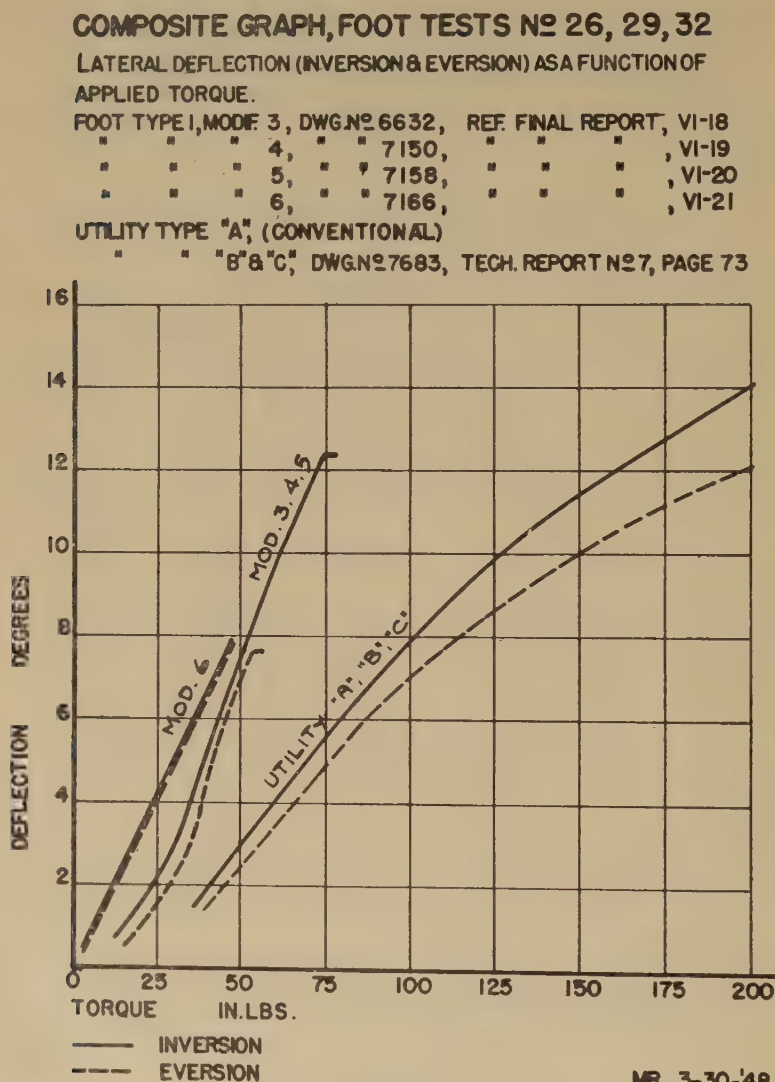


FIGURE 22.

offered by the suction socket *per se* and so far has not been practically applied. However, a cross-linkage system supplementing the pantograph arrangement for interrelated motion between the ankle and knee was suggested by Oliver.[27]

An adaptation of Oliver's cross-linkage is shown in FIGURES 4 and 5. The

cross-linkage, as modified, permits initial knee flexion in the order of 14° when plantar flexion of approximately 20° occurs. Further, the energy which is stored in the heel bumper upon heel contact is returned to the

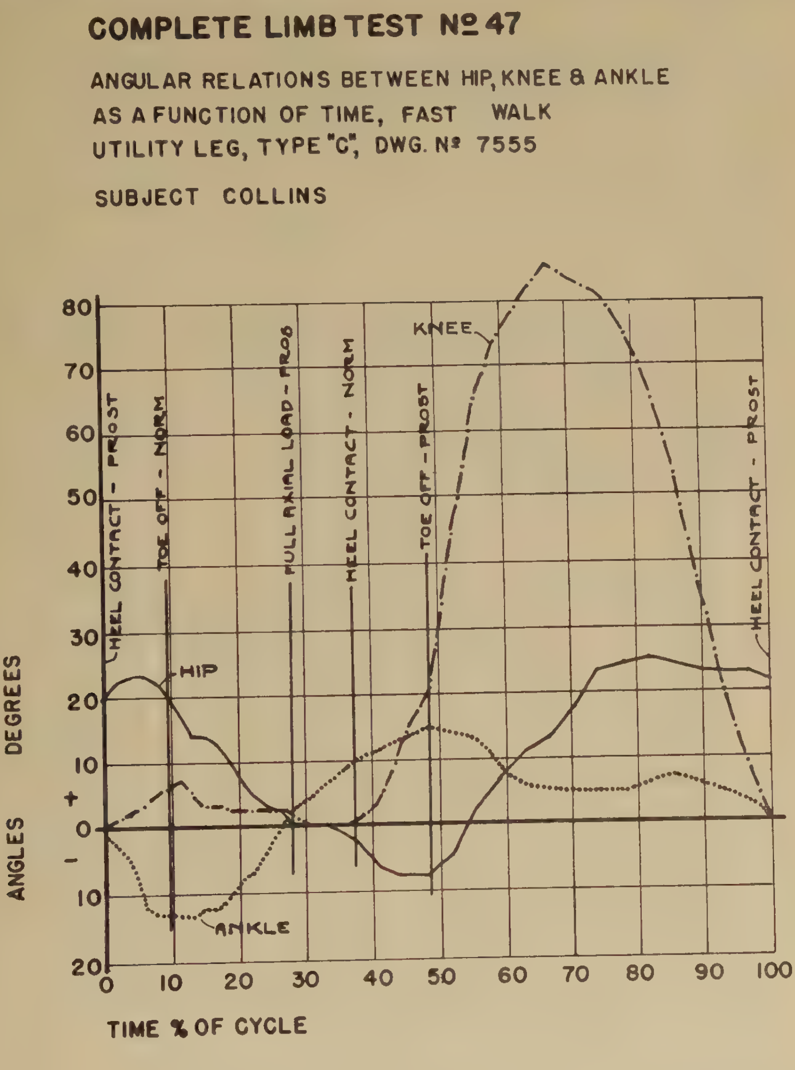


FIGURE 23.

prosthesis at a uniform rate as knee extension occurs during the stance phase. When the hydraulic system is inoperative, however, initial knee flexion does not occur, the prosthesis remaining mechanically stable.

The application of shock-absorbing media becomes much more important

where rapid deceleration occurs. This is especially true at the ankle during load service requirements.

Modifications of the Bly, Mare Island (FIGURE 19), and the Trautman type ankles have been experimented with, resulting in an ankle and foot

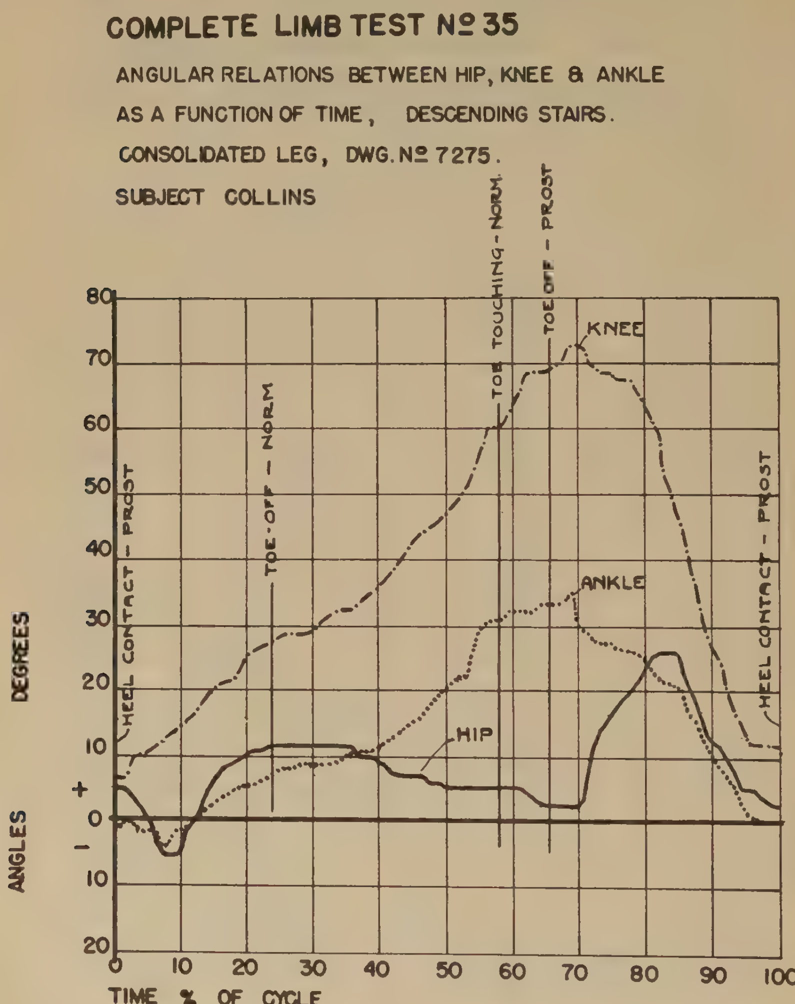


FIGURE 24.

design having characteristics for plantar flexion as in FIGURE 20, toe flexion as in FIGURE 21, and lateral deflection as in FIGURE 22.

Based upon evaluation of University of California data contained in Eberhardt and Inman's FIGURE 12,* foot and ankle characteristics per curves marked "Utility A, B, C," FIGURES 20, 21, AND 22 were selected for experimental and field test purposes.

* See p. 1227.

As a result of the evaluation of fundamental data and consolidation of preliminary design applications, a prosthesis has been developed which is now in the process of field testing. The functional angular limits are as follows:

Controlled knee flexion within	110°
Weight bearing initial knee flexion on heel impact due to cross-linkage when 20° plantar flexion occurs	14°
Dorsiflexion	35°
Plantar flexion	20°
Lateral motion—Eversion	20°
Inversion	20°
Horizontal rotation—Abduction	25°
Adduction	15°

Rotational studies of the first two prototypes are indicated on FIGURE 23 for fast walking, and on FIGURE 24 for descending stairs.

It will be noted that the principal functional difference between the prosthetic device and the normal leg is in the lack of ankle extension. Investigations are now in process for determining the amount of energy available upon heel impact and the amount of energy that can be obtained due to the kinetic energy of the body during the stance phase, up to and including heel contact of the normal leg, so as to provide ankle extension.

Bibliography

1. ELFTMAN, H. 1934. The axis of the human foot. Science **80:** 484.
2. ELFTMAN, H. 1935. Chimpanzee and human feet in bipedal walking. Am. J. Phys. Anthropol. **20:** 69–79.
3. ELFTMAN, H. 1938. The measurement of the external force in walking. Science **88:** 152.
4. ELFTMAN, H. 1939. Forces and energy changes in the leg during walking. Am. J. Physiol. **125:** 339–356.
5. ELFTMAN, H. 1939. The function of muscles in locomotion. Am. J. Physiol. **125:** 357–366.
6. ELFTMAN, H. 1939. The rotation of the body in walking. Arbeitsphysiol. **10:** 477–484.
7. ELFTMAN, H. 1939. The force exerted by the ground in walking. Arbeitsphysiol. **10:** 485–491.
8. ELFTMAN, H. 1939. The function of the arms in walking. Human Biol. **11:** 529–535.
9. ELFTMAN, H. 1940. The work done by muscles in running. Am. J. Physiol. **129:** 672–684.
10. ELFTMAN, H. 1941. The action of muscles in the body. Biol. Symp. **3:** 191–209.
11. ELFTMAN, H. 1943. Experimental studies on the dynamics of human walking. Trans. N. Y. Acad. Sci. **6**(1): 1–4.
12. ELFTMAN, H. 1944. The bipedal walking of the chimpanzee. J. Mammal. **25:** 67–71.
13. ELFTMAN, H. 1945. The carrying angle of the human arm as a secondary sex character. Anat. Rec. **91:** 49–52.
14. ELFTMAN, H. 1945. Torsion of the lower extremity. Am. J. Phys. Anthropol. N. S. **3:** 255–265.
15. ELFTMAN, H. 1945. The orientation of the joints of the lower extremity. Bull. Hosp. J. Dis. **VI:** 139–143.
16. UNIVERSITY OF CALIFORNIA. Fundamental studies of human locomotion and other information relating to design of artificial limbs, Report to Nat. Res. Council, Committee on Artificial Limbs, covering the period September 1945–June 1947.
17. PARMELEE, D. D. U. S. Patent 37,637, February 10, 1863, and Reissue Patents 1,907 and 1,908, March 21, 1865.
18. NORTHWESTERN UNIVERSITY. Translations and prior art. Progress Report 13 on Analysis of Existing Prosthetic Devices, Contract W-49-007-MD-347.

19. Little, E. M. 1922. Artificial Limbs and Amputation Stumps. H. K. Lewis, London; Blakiston, Philadelphia.
20. Martin, F. 1924. Artificial Limbs. International Labor Office, Geneva.
21. Thomas, A. & C. Haddan. 1945. Amputation Prosthesis. Lippincott. Philadelphia.
22. Springer, J. (Publisher) 1919. Ersatzglieder und Arbeitshilfen. (By some 30 authors.) Berlin.
23. Gocht, H., R. Radike, & F. Schede. 1932. Künstliche Glieder. Enke, Stuttgart.
24. Mommsen, F. & K. Büchert. 1932. Künstliche Glieder. Enke, Stuttgart.
25. Murphy, E. F. 1946. Problems in design of prosthetic devices, Mech. Eng. July: 632–636.
26. Catranis, J. G. Artificial limb development for above-knee amputees including mechanical and hydraulic knee locks; suction socket and suction socket controls; knee lock controls operated by hip motion, stump muscles and foot position; toe pick up and foot providing lateral, plantar and dorsiflexion. C. C. Bradley & Son, Inc., Catranis, Inc. Sub-contractor's Final Report to Nat. Res. Council, Committee on Artificial Limbs, covering the period March, 1946 through June, 1947.
27. Oliver, W. C. The development of a hydraulically operated artificial leg for above-knee amputations. Adel Precision Products Corporation. Subcontractor's Final Report to Nat. Res. Council, Committee on Artificial Limbs, covering the period July 15, 1946 through June 30, 1947.

A METHOD FOR KINEMATIC ANALYSIS OF MOTIONS OF THE SHOULDER, ARM, AND HAND COMPLEX

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The literature of kinesiology, body mechanics, physical anthropology, and osteometry presents an array of facts about muscle, bone, and tendon relationships in the human shoulder, arm, and hand, both in the static and dynamic state. Generally, these expositions are descriptive and qualitative. Only on certain portions of the mechanism have precise geometrical and quantitative data been obtained. There is lacking from these sources a comprehensive but practically feasible scheme for analysis of the kinematics of the system. The methods of motion study, widely applied to occupational and other human activities, similarly have failed to provide the desired rationale. While the therblig and similar techniques of motion study offer a semi-quantitative approach, they involve a mixture of hand-arm movements and job elements which describe the biokinematics only in a very general sense.

The need for a practical but precise method for shoulder-arm-hand motion analysis immediately arises from research to establish the functional requirements for arm and hand prostheses. Here, the substitution of mechanical equipment for the lost members, enormously complicated by the limited number of controls available from shoulder harness, muscle tunnel, and accessory mechanical controls, poses for the engineer the perplexing problem of putting the functional regain where it will be most effective. It is necessary, for his guidance, to establish the frequency and extent of motions in the natural mechanism as they are involved in the performance of the common activities of daily living. Such data, therefore, figure prominently in the design and evaluation of the prosthesis.

A workable method for kinematic analysis should not long await application to many fields of human biology. It opens the way to dynamic analysis of all types of manual work. The calorimetric techniques for measurement of the energy in such work have long been recognized to lack the specificity and sensitivity necessary for a scientific formulation of the vast array of light activity types. They fail to differentiate clearly the work done in moving the body structures from that done against external loads. Hence, it is expected that the physical analysis of biomechanics will contribute in a very fundamental way to the investigation of human energetics in manual work.

The purpose of this paper is to describe a method of kinematic analysis of the motions of shoulder, arm and hand. There are six steps involved, as follows:

(1) Measurement and calibration of the standard experimental subject.
(2) Fitting of the subject with visual landmarks.
(3) Cinematography of the subject performing the activities under study.
(4) Obtaining the Cartesian earth coordinates of the visual landmarks

from selected frames of the developed film, and correcting these co-ordinates for parallax.

(5) Analysis of the coordinate data to yield the axes and angles of the idealized kinematic system.

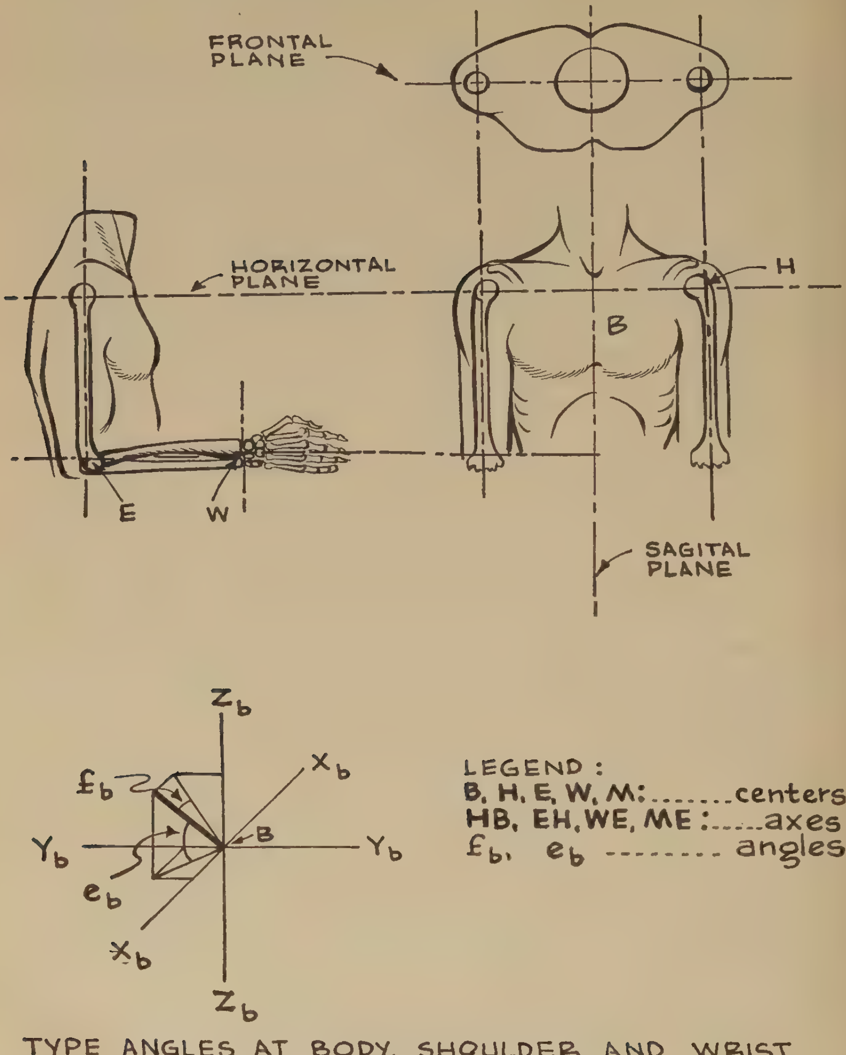

FIGURE 1. Axes and angles of the idealized system.

(6) From serial frames, obtaining angular velocities and accelerations of the members of the kinematic system.

The Idealized Kinematic System

Although there are 14 bones whose inter-articulations contribute to the motions in the shoulder-arm-hand complex, an idealized system, composed

of four levers, rotating on four centers through a total of nine angles, may be considered to simulate the mechanism. FIGURE 1 presents the details of this system for the right shoulder, arm, and hand.

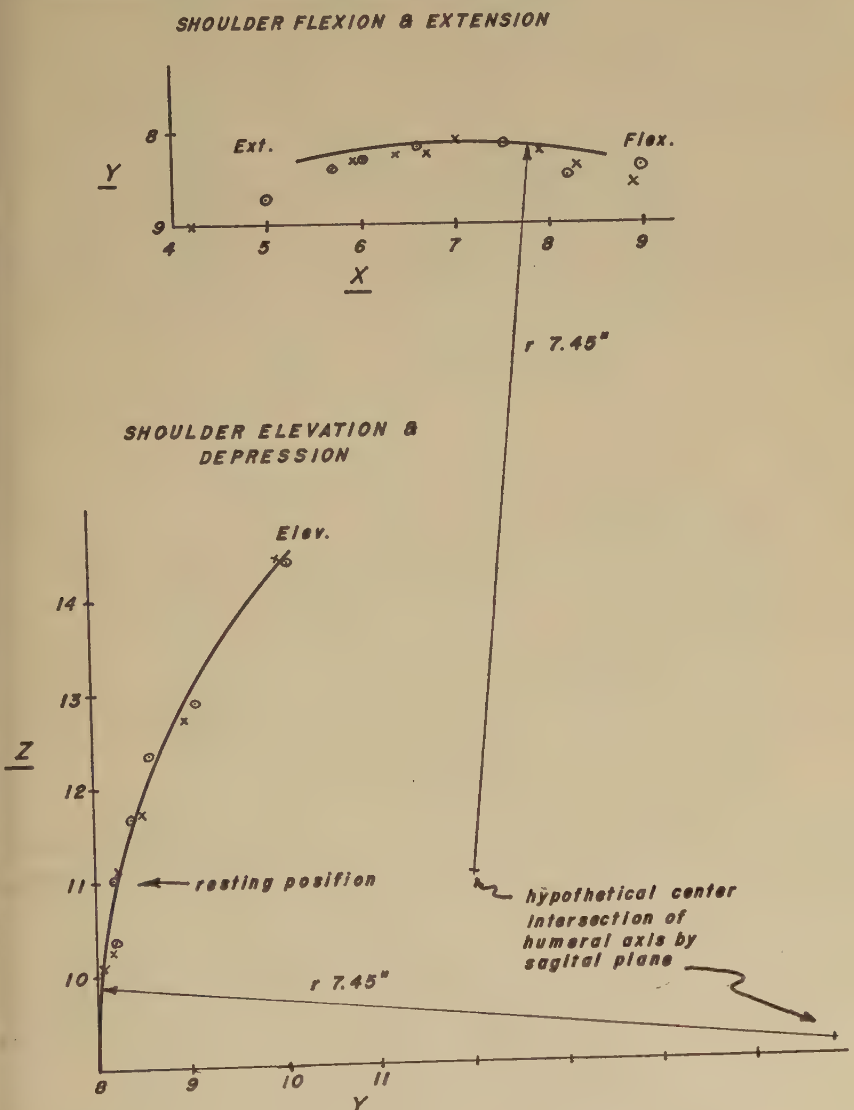

FIGURE 2. Shoulder motions—plotted path, acromioclavicular landmark.

The validation of the idealized system depends upon the correlation of information from several sources to picture the various centers and axes. These sources include: (a) direct measurements of external counterparts; (b) X-ray views of parts of the system to show relationships between visual landmarks and the centers and axes of the idealized system; and (c) plots

of the paths made by distal points in the axes while rotating on the assumed centers. In most cases, data drawn from one source may be directly compared with those from another source, thus providing general validation of the assumptions and indicating the limits of motion within which they hold without exceeding acceptable error.

The Shoulder Axis. Center: B, intersection of the humeral center axis (standard posture) by the sagittal plane. Axis: BH, sagittal plane to humeral center. Angles: f_b, flexion-extension; e_b, elevation-depression.

This part of the system is the most difficult to define because of the complexity of its skeletal components, which have three articulations, sterno-clavicular, acromio-clavicular, and coraco-humeral, and also the peculiar muscular suspension of the scapula. It is beyond the scope of this paper to discuss anatomy in detail, but evidence is presented to show that, within common limits of motion, the distal part of the system may be taken to act

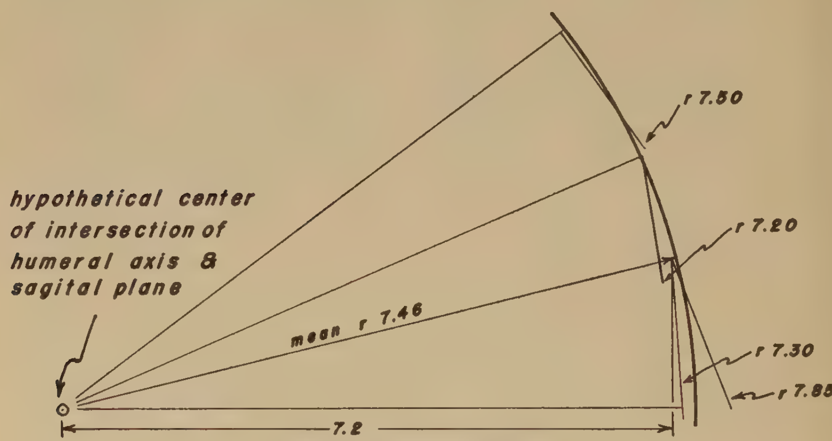

FIGURE 3. Locus of humeral center.

like a hypothetical lever upon a hypothetical center, free to move through two angles. Thus, FIGURE 2 shows that a point just over the acromio-clavicular joint (L_h) describes arcs of radius 7.46 in. in the horizontal plane and frontal planes.

The measurements and constructions by which this system was established are detailed in FIGURE 3. From X-ray views it was established that the humeral center, H, with subject in standard posture, is 0.26 in. lateral to and 1.75 in. below the landmark, L_h. Constructions from these views show relations of L_h and H at three positions of the arm elevation. It is noted that the path of H about B varied by an average of 0.21 in. radius. This is undoubtedly caused by differences in the setting of the scapula. There appears to be no simple manner, at present, of reducing this variability, and the average value of radius, 7.46, is accepted.

The Arm Axis. Center: H, humeral center. Axis: HE, elbow center to humeral center, as established above. Angles: f_h, flexion-extension; e_h, elevation-depression; t_{HE}, medial and lateral torsion.

The distal end of HE is defined as the midpoint on the axis through the

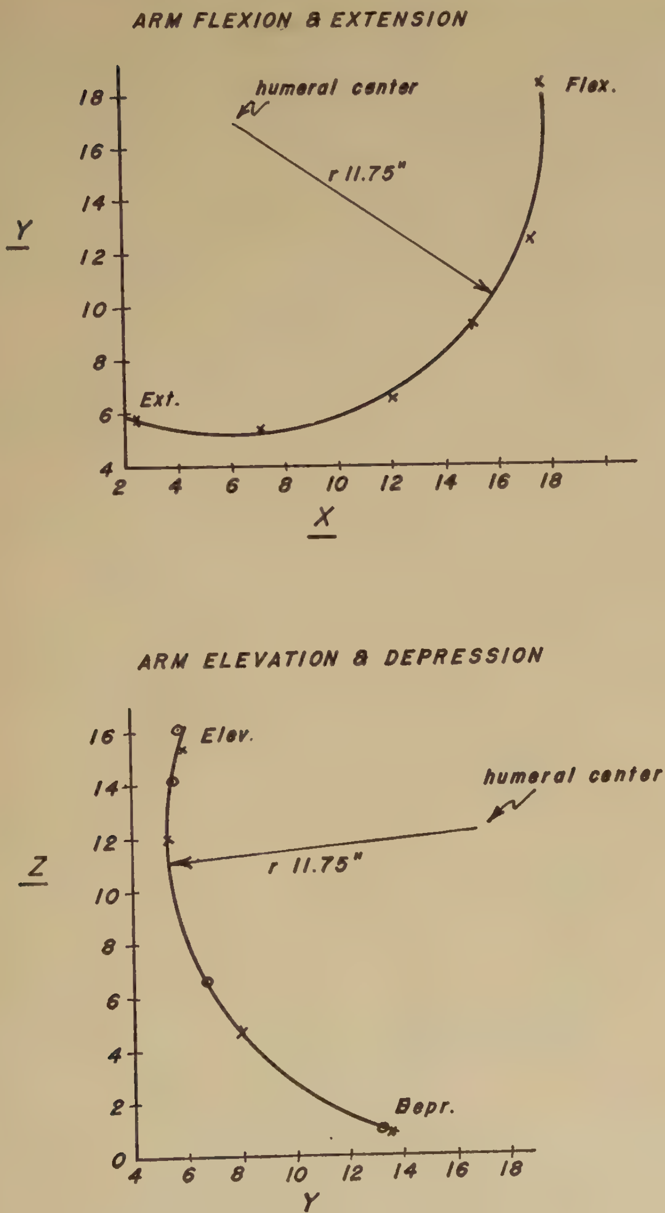

FIGURE 4. Humerus rotations—plotted path, lateral epicondyle.

medial and lateral epicondyles of the elbow. Its length, as verified in standard posture calibration by the difference between L_hE and L_hH, is 11.75 in. Rotations of this member in the horizontal and frontal planes yield plots of the path of the epicondyle which verify the assumptions, both of axis center and axis length. FIGURE 4 shows departures from the radius

not greater than 0.25 in. Check measurements on the torsional rotation of *HE*, displayed in FIGURE 5, are compatible with the assumption of an axis through *HE* as defined, although the demonstration is not completely definitive because of the difficulty of obtaining the true locus of the humeral head during this motion.

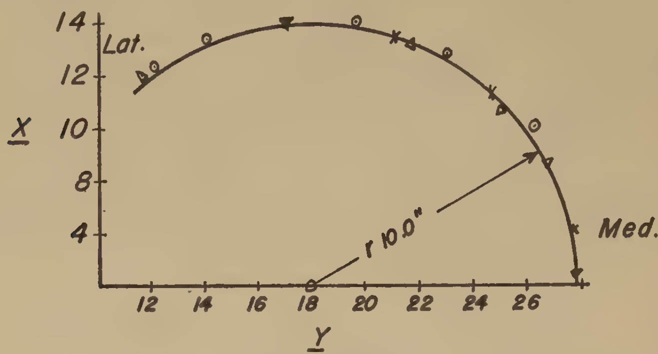

FIGURE 5. Arm torsion.

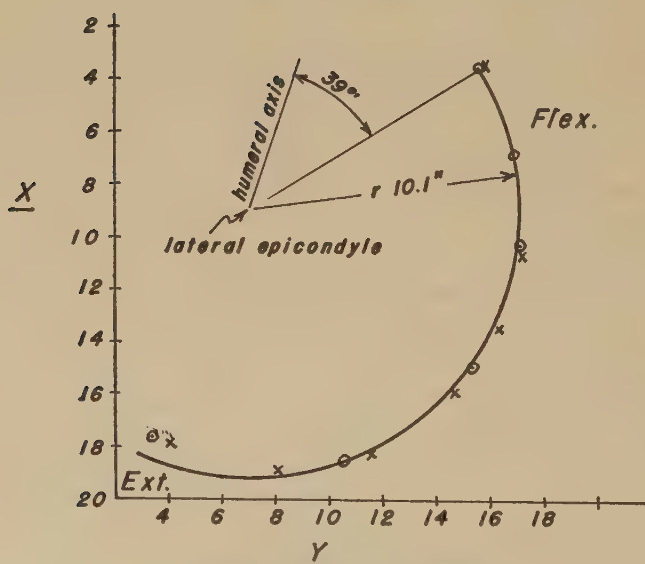

FIGURE 6. Forearm flexion—extension.

The Forearm Axis. Center: *E*, the midpoint of the biepicondylar diameter. Axis: *EW*, axis through wrist and elbow centers. Angles: f_e flexion-extension; t_{EW}, supination-pronation.

The distal end of *EW* is defined as the intersection of the major and minor diameters of the wrist at the plane of the proximal aspect of the carpal-radial-ulnar articulation. The latter was located in X-ray views of our subject's wrist at 0.25 in. distal to the mid-styloid point. FIGURE 6 shows the path of the mid-styloid about the biepicondylar axis. Because of a

pronounced carrying angle, the plotted points during the later 30° of extension fall on shorter radius. Until a detailed correction for this effect can be worked out, it is necessary to limit forearm extension so that this effect of carrying angle does not introduce spurious results.

The path of an artificial projection normal to EW at W, illustrated in FIGURE 7, shows that deviations from a planar surface of revolution are less than .12 inches, except at extreme pronation, where they may be as large as .25 inches. While the structure and articulations of radius and ulna of the forearm suggest torsion about the ulna distally, it should be pointed out

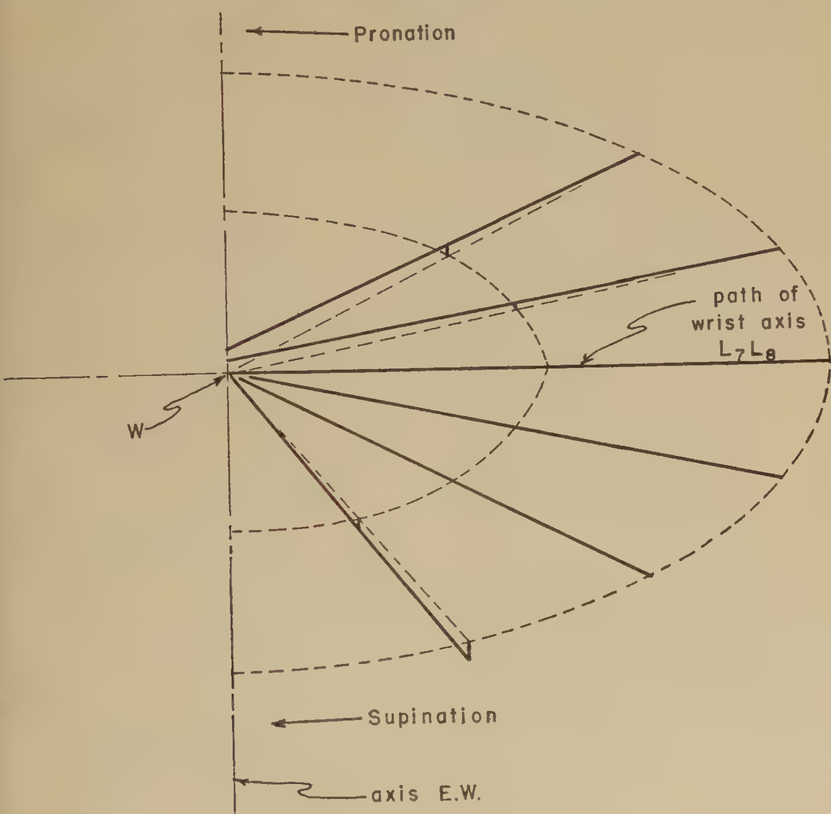

FIGURE 7. Forearm rotation.

that the assumption of forearm rotation about the axis EW is not incompatible with the facts.

The Hand Axis. Center: W, at the center of wrist cross section at the plane of the radial-ulnar-carpal articulation. Axis: WM, hand point to wrist center. Angles: f_w, flexion-extension (volar-dorsal); e_w, abduction-adduction (radial and ulnar flexion).

With W defined above, the only remaining locus to specify is M, the hand center. This is postulated as a point on the palmar pad superficial to the metacarpal-phalangeal joint of the third finger. It is obtained by a calibra-

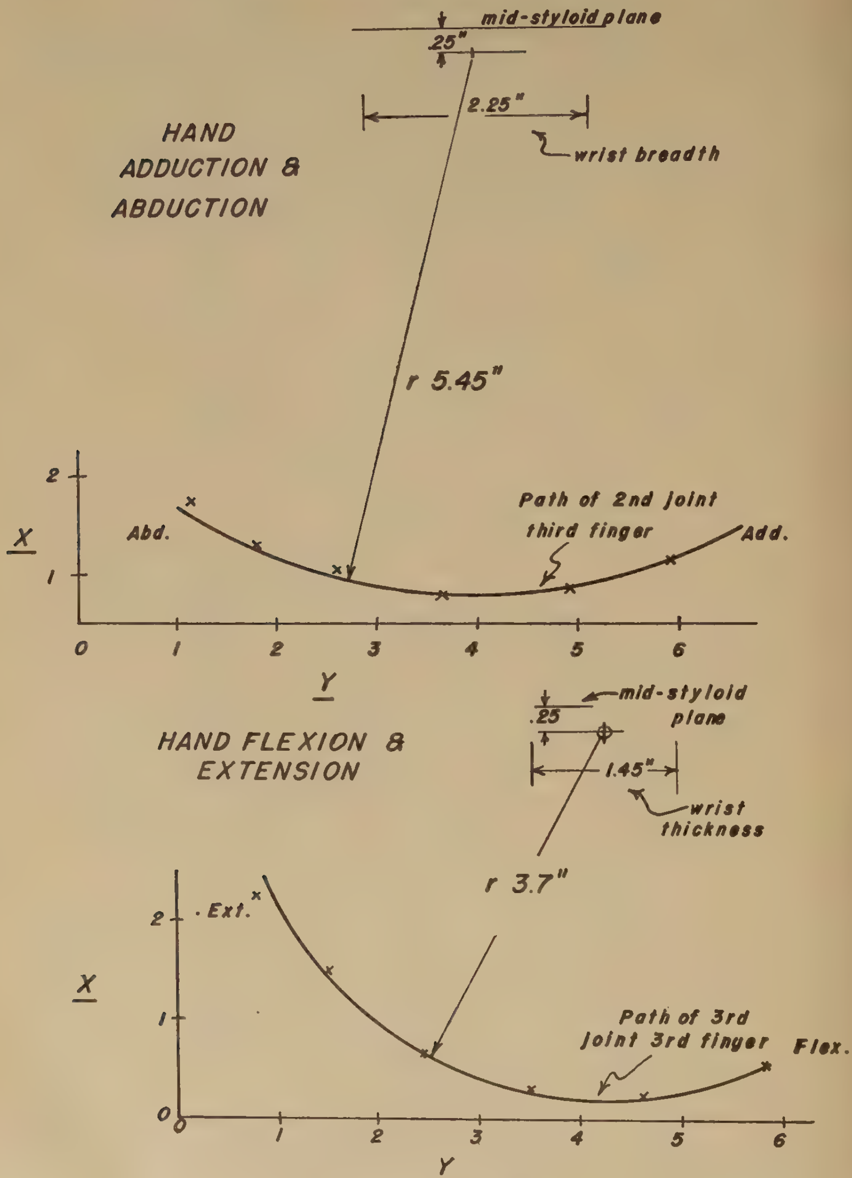

FIGURE 8. Hand rotations.

tion vector established between L_m and M in the resting hand. FIGURE 8 verifies the locus of W.

The Visual Landmark System

Since the essential loci of centers and axes of the idealized system cannot be seen, the visual landmarks and their geometric relationships with the

system are an indispensable feature of the method. The landmarks are shown in their positions on the subject in FIGURE 9.

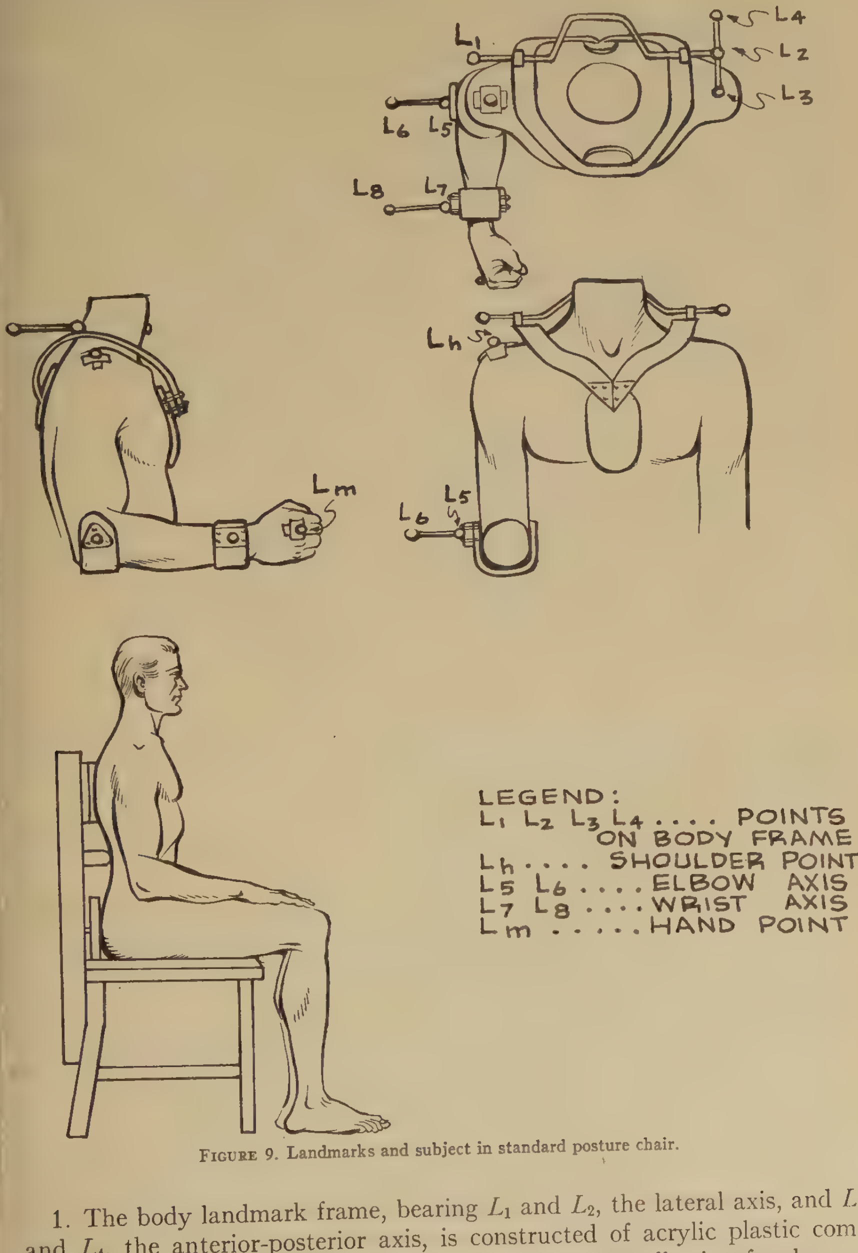

FIGURE 9. Landmarks and subject in standard posture chair.

1. The body landmark frame, bearing L_1 and L_2, the lateral axis, and L_3 and L_4, the anterior-posterior axis, is constructed of acrylic plastic components with footings on sternum and thoracic spine allowing freedom of head and shoulders without displacement from the thorax. The standard posture chair, shown in FIGURE 9, permits the establishment of a definable

and reproducible body alignment which serves as the basis of the geometric constructions. The exact setting of the landmark frame, relative to the body, and relative to the body in the chair, established by preliminary measurements, is utilized each time the subject is prepared for motion analysis. The frame is then strapped and taped into position.

2. The shoulder point, L_h, is a simple plastic sphere taped to the shoulder just over the acromio-clavicular point. In our subject, as in most individuals, this point can be located by palpation just lateral to the distal prominence of the clavicle. X-ray views indicate that about 0.25 in. of flesh separate it from the superior margins of the bones. An advantage of this location is the lack of any considerable skin migration on movement which might disturb its relationship to the joint locus. FIGURES 9 and 3 show how this landmark has been related to H and BH of the idealized system.

3. The elbow landmark, L_5L_6, is positioned in the biepicondylar axis just superficial to the lateral epicondyle. Since there is considerable skin migration at this point caused by forearm flexion, a plastic shell has been fashioned to fit on the dorsal aspect of the forearm, running from the olecranon about 3 in. distally, and turning up the sides to bear over the medial and lateral epicondyles. By strapping and taping in place, this shell holds L_5 and L_6 in their proper locations with negligible variation.

4. Landmarks L_7 and L_8 define an axis through the short diameter of the wrist, normal to EW and in the plane of the radio-carpal joint. They are fixed on a rod which is joined to a molded plastic bracelet.

5. L_M, like L_S, is a plastic sphere taped to the skin. Its location is just over the metacarpal-phalangeal joint of the third finger.

Angles and Reference Coordinates

Attention has been focused upon the motion of each lever upon its center in relation to the part immediately proximal to it. This, and the selection of angles, is dictated by a number of considerations:

(a) The muscles of the shoulder-arm-hand complex, with several minor exceptions, are one-joint muscles, and their activity is properly gauged by the movement of a part relative to its proximal part.

(b) Flexion, extension, torsion, abduction, and adduction angles are traditional in the anatomical nomenclature and relate fundamentally to the interactions of muscles with the skeletal levers. It will be obvious that other angles, such as those of a spherical system, could be used, and that relations between parts not immediately contiguous could be sought, but these are not essential to the present applications. In any case, other angles and interrelationships could easily be derived from the basic constructions.

The basic plan is to construct, at each center in the idealized system, reference coordinate systems to evaluate the axis rotations in terms of the angles made with the coordinate systems. An exception to this is the forearm, which rotates on the elbow as a simple hinge. Thus, angles of the type f and e are measured from their projections upon the planes of reference. This is considered to represent most closely the physical facts of relative motion at joint surfaces and lines of tension of the operating muscle groups. The constructions required are defined in TABLE 1.

Photography in the Earth Coordinate System

The subject, landmarks in place, is photographed within the earth coordinate system. The details of this setup are shown in FIGURE 4. By means of a direct front view, and side and top views through mirrors, the position of each landmark in space may be evaluated according to the earth system of coordinates. Two views of apparent coordinates of each landmark are obtained, thus X from side and top, Y from front and top, and Z from front and side. In practice, both coordinates are read when visible. Often, one view is obscured by some body part, so that the availability of the other view is important. When both coordinates are visible, they permit a useful cross-check.

TABLE 1

Axis	*Angles*	*Reference Coordinates (right-handed convention)*
Shoulder	f_b e_b (Note: t_{BH} assumed not to exist)	Body coordinate system: Landmark axes L_1L_2 and L_3L_4 become Y_b and X_b axes through B as origin; Z_b is defined as normal to both and passing through B.
Arm	f_h e_h	Shoulder coordinate system: Z_s passes through H, is normal to BH, and in the plane of Z_b and HB. Y_s is an extension of BH. X_s is defined as normal to BH and Z_s with origin at H.
	t_{HE}	Normal to the plane defined by two positions of HE is constructed. The difference in the angles between this normal and the elbow axis, L_5L_6, in the two positions is the angle of torsion.
Forearm	f_e	Included angle between HE and EW.
	t_{EW}	L_5L_6 is projected upon the transverse plane X_mZ_m of the wrist coordinate system. The angle between this projection and the axis X_m is the angle of torsion.
Hand	f_m e_m	Wrist coordinate system: Y_m is the extension of EW. X_m is given by the landmark axis L_5L_6 through W and normal to EW. Z_m is defined as normal to Y_m and Z_m and passing through W as origin.

Not shown in FIGURE 10 are the coordinate scales for each of the views. These were laid off by sighting through a transit, set at the camera position. Thus, the earth coordinate system, as shown in FIGURE 10, was first constructed, then scales were laid off in two axes for each view, *e.g.*, front, and side and top through mirrors. It should be pointed out that the corrections incorporated in these scales merely serve to establish equivalence with the true earth coordinates at the earth reference planes. Thus, they give values according to the apparent earth coordinates.

From such apparent coordinates, it is then necessary to correct for parallax to obtain the true coordinates of a landmark point. There are 8 possible

combinations of apparent coordinates from the three views. Equations for true XYZ's from apparent XYZ's are required for each combination. As an example, X from the top, and Y and Z from the front are evaluated by the equations:

$$X = X_t'\left(\frac{Z}{d_t} + 1\right)$$

$$Y = Y_f'\left(\frac{x}{d_f} + 1\right)$$

$$Z = Z_f'\left(\frac{x}{d_f} + 1\right)$$

where, XYZ = true coordinates
$X'Y'Z'$ = apparent coordinates
d_f = normal distance, camera lens to front earth reference plane
d_t = normal distance, camera lens to top earth reference plane, after reflection from top mirror.

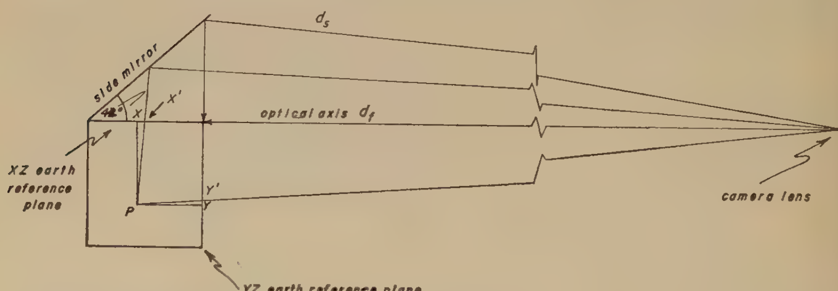

FIGURE 10. Photographic and earth coordinate system (plan view). For side elevation, read Z', Z for Y', Y, top mirror for side mirror, d_t for d_s, plane XY for plane XZ.

Simultaneous solutions for unknowns yield the equations:

$$X = \frac{X_t' d_f(d_t + Z_f')}{d_f d_t - X_t' Z_f'}$$

$$Y = \frac{d_t Y_f'(X_t' + d_f)}{d_f d_t - X_t' Z_f'}$$

$$Z = \frac{d_t Z_f'(X_t' + d_f)}{d_f d_t - X_t' Z_f'}$$

The motions are photographed with a Mitchel camera* at 24 frames per second. A lens of 75 mm. focal length frames the three views at the average lens-object distance of 31 feet. After developing, negatives may be read directly or positively printed. The apparent coordinates are read from an editing projector† fitted with a rectangular locator upon the screen, so

* Mitchel high speed 35 mm. This camera is on loan from the U. S. Veterans Administration. Acknowledgment is made with appreciation.
† Model DVP, Moviola Manufacturing Co.

that points in space can be measured from the side scales. Coordinates are read to 0.2 in.

Analysis by a Mechanical Simulator

In a previous report,* a device known as the Kinematic Analyzer was described. This apparatus is a half-scale system of joints, members, and scales which is capable of reproducing the major joint rotations of the shoulder, arm, forearm, and hand. Landmarks are placed on the analyzer

TABLE 2

ANTHROPOMETRIC DATA

Sitting heights	*(inches)*	*Girths*	*(inches)*
Manubrial	22.4	Chest	35.5
Xyphoid	15.0	Midarm (right)	10.5
Acromion (right)	23.6	Midforearm (right)	10.25
Crown	34.8		
7th cervical	25.5		

Lengths	*(inches)*
Biacromial (lateral)	16.5
Manubrium (anterior-posterior)	6.3
Xyphoid (anterior-posterior)	7.2
Chest width	11.6
Bi-epicondylar (right)	2.50
Wrist breadth (right)	2.25
Wrist thickness (right)	1.45
Humeral (right)	11.75
Ulnar (right)	10.10
Hand breadth (right)	3.3

Calibration vectors (with subject in standard posture)

Body frame: (referred to B as origin)

	X_b	Y_b	Z_b
L_1	−2.5	+6.0	−4.1
L_2	−2.5	−6.0	−4.1
L_3	+2.5	−6.0	−4.1
L_4	−7.5	−6.0	−4.1

Shoulder point:

L_h to H $\quad dX_b = 0$, $\quad dY_b = +0.25$, $\quad dZ_b = +1.75$

Elbow axis:

L_5 to E 1.6; L_6 to E 6.6 — both in line normal to HE and EW

Wrist axis:

L_7 to W 1.75; L_8 to W 5.75 — in line normal to EW and transverse dorsum of wrist

in locations which bear the same relationship to its lever systems which the landmarks of the human subject bear to his skeleton. When the analyzer is adjusted, by use of the coordinates of the landmarks, the angular relationships between its members are comparable to similar relationships in the subject.

Calibration of the analyzer to the pertinent dimensions of the subject requires the setting of segment lengths and landmark positions according to the data given in TABLE 2.

* "Studies to determine the functional requirements for hand and arm prosthesis," Report to NRC (1947). Dept. Eng., Univ. Calif., Los Angeles.

The analyzer is positioned upon a horizontal plane table, laid off with rectangular grid lines representing the X and Y of the earth coordinate system. Z distances are found with point locators, set at the appropriate X and Y. With point locators in place, the analyzer is adjusted to bring its landmarks into the indicated locations. To do this, the segments and joints must assume the angular geometry of the original anatomical posture. The analyzer angle scales, scribed to 2 degrees, now indicate directly the desired angles.

Analysis by Calculation

It suffices here to describe the mathematical procedure only in general terms.* Since the axis lengths of the idealized system are known from measurements given above, the anatomical angles represent the chief goal of the calculation.

Shoulder, Arm, and Hand Systems. It is clear that the desired angles f and e may be calculated after first transforming each axis segment to its corresponding reference coordinate system. This raises the following fundamental problem:

Given: any axis segment, say the arm, HE, in terms of earth coordinates from photographic data.

To Find: Components of HE in any other coordinate system, say the shoulder coordinate system.

The shoulder coordinate system will be known in terms of earth coordinates:

$$\begin{aligned} i_h &= X_{ih}i + Y_{ih}j + Z_{ih}k \\ j_h &= X_{jh}i + Y_{jh}j + Z_{jh}k \\ k_h &= X_{kh}k + Y_{kh}j + Z_{kh}k \end{aligned}$$

$\overline{HE}$ in earth components will be:

$$\overline{HE} = X_h i + Y_h j + Z_h k$$

Thus HE, in components of the shoulder system will be:

$$\begin{aligned} \overline{HE} &= \overline{HE}\cdot i_h i_h + \overline{HE}\cdot j_h j_h + \overline{HE}\cdot k_h k_h \\ \overline{HE} &= (X_h X_{ih} + Y_h Y_{ih} + Z_h Z_{ih})\, i_h + \\ &\quad (X_h X_{jh} + Y_h Y_{jh} + Z_h Z_{jh})\, j_h + \\ &\quad (X_h X_{kh} + Y_h Y_{kh} + Z_h Z_{kh})\, k_h \end{aligned}$$

Forearm Flexion-Extension. The included angle between HE and EW may be calculated directly without transformation of coordinate systems.

Torsion Angle of the Arm. In the case of arm torsion, consider two positions of $\overline{HE}$ in space $\overline{HE}_1$ and $\overline{HE}_2$. Let $\bar{n} = \overline{HE}_1 \times \overline{HE}_2$. If an axis $\bar{A}$, through $\overline{HE}$, and normal to it, rotates about $\overline{HE}$ through angle t_{HE} from

* Detailed calculation procedure may be obtained from the authors.

$\bar{A}_1$ to $\bar{A}_2$, and if

$$t_1 = \angle\,{}^{\bar{n}}_{\bar{A}_1} \qquad t_2 = \angle\,{}^{\bar{n}}_{\bar{A}_2}$$

then, $t_{HE} = t_2 - t_1$. Here, $\bar{A}$ is the elbow axis, L_5L_6, and torsion between positions 1 and 2 is obtained by computing the difference between t_1 and t_2.

Torsion Angle of the Forearm. This angle, pronation-supination, is directly obtained from the change in angle between elbow axis, L_5L_6, and wrist axis, L_7L_8, in any two positions.

HUMAN ENGINEERING PROBLEMS IN SERVICE TESTING OF PROSTHETIC DEVICES

By Lawrence Edwin Abt

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For the past three years, under the sponsorship of the Advisory Committee on Artificial Limbs of the National Research Council and with funds supplied by the Federal Government, a comprehensive program in human engineering research has been under way. We have read here reports from a number of leading research workers in this area. For the most part, these papers have considered aspects of some of the fundamental work which has been going on in the biomechanics of the upper and lower human extremities.

Concurrently with the more basic studies, as is evident from Mr. Catranis's paper, engineers have been undertaking extensive applied engineering research which has as its objective the development and design of more efficient prosthetic devices for the upper and lower extremities. Over the past several years, a number of exceptionally promising artificial limbs of one kind or another have emerged, and several of the devices have already been recommended to the Veterans Administration for general adoption. Members of the Advisory Committee on Artificial Limbs have moved with due humility and caution, however, in recommending other devices, for failures in this area are exceptionally costly to the Government and, what is more important, unusually disheartening to amputee veterans.

Because of a basic human engineering approach to prosthetic problems which had already been developed in the Research Division of the College of Engineering at New York University in work with above-the-knee amputees, late in the fall of 1947, the Advisory Committee on Artificial Limbs induced our research staff to embark upon an intensive and continuing program of service testing of promising prosthetic devices which had been developed under the Committee's sponsorship.

In undertaking research in this new area, we soon found that we were confronted with manifold problems in human engineering—problems, I might say, which had apparently been overlooked previously. In our earlier work, we had already recognized the necessity of paying attention to and learning to understand the role of the human member of the man-machine system which exists when a prosthetic device is fitted to an amputee. Our new tasks demanded that we devise techniques which would permit us to study the functions and role of the machine member—the prosthesis itself—of this system. Such a study had to be carried on with the problems of the amputee himself ever in mind.

Earlier, our research with above-the-knee amputees had pretty well convinced us that the efficiency with which an amputee can use an artificial limb is in ratio to the extent to which the prosthetic device becomes functionally a part of his body and personality. Among other things, this process requires the amputee to accept a total loss of function, imposed by the amputation, and substitute for it the more limited functions made possible by the prosthetic attachment. It is evident, upon reflection, that this in-

volves a complicated psychological process, by means of which the artificial limb becomes more or less fully integrated into the individual's self-concept and body image. We can only guess, at this stage of inquiry, as to the nature of such processes. It seems clear, however, that they entail a process of new learning, in the widest sense, as well as significant reorganizations of the self-system.

Under such circumstances, the selection of appropriate pilot wearers for the prosthetic devices entrusted to us for evaluation looms up as a matter of major concern. Each pilot wearer who participates in the service testing program must be required to meet certain minimum standards of orthopedic, prosthetic, and psychological acceptability. Our principal psychological considerations entering into the selection process of subjects have been the level of adjustment which the subject has been able to achieve with respect to his old prosthesis and the efficiency with which he can use it. A determination of adjustment has been arrived at by means of several established psychological procedures (such as clinical interviews, tests of intelligence, temperament, personality, and attitude scales), which have as their function that of allowing the psychologist to uncover the predominantly positive feelings and attitudes of the subject and his major negative attitudes and feelings. Efficiency in the use of the old prosthesis has been determined by observation of the amputee's gait and his ability to pass a number of fairly simple and quite realistic achievement tests.

It is vital that careful selection of pilot-wearer subjects be made so that the man-machine system which is under study will function at its highest level of efficiency. If we are relatively sure of a fairly constant capacity on the part of the amputee, major variations in the functional efficiency of the prosthetic device may then be regarded as stemming rather from its mechanical characteristics and its limitations than from basic physical and temperamental qualities of the experimental subject. The problem of holding relatively constant the human member of this man-machine system is not one to be taken lightly, and I am of the opinion that it demands of the biomechanical team charged with this responsibility unusual devotion and concern at all times. In the earliest stages, it is essential to orient the amputee subject to the major purposes of the service testing program, and to develop and maintain in him a high level of motivation toward the task during the period of his participation in the study.

Our experience to date has amply demonstrated that, unless this is done, one cannot have much confidence in the data which are collected. The same situation exists, of course, in the matter of experimental design of the research project. In developing such an experimental design, for example, we have to know with a relatively high order of probability that any difficulties which develop in the man-machine system are due principally to defects in the device and not essentially to any characteristics of the pilot wearer. The whole problem becomes enormously more complicated, and therefore more challenging, when one is concerned not with the addition of one prosthetic device to the amputee but with the possibility of attaching several, each of which must necessarily be studied as independently as possible.

This particular problem finds direct expression in a current study. We

are in the process of evaluating several new artificial legs for above-the-knee amputees which have to be attached to the body by a new technique known as the suction socket. One wants to try to ascertain at the very beginning, in such a study, how much of the efficiency of performance of the amputee subject is due to the suction socket and how much due to the new prosthetic device, assuming that it will be possible to hold the amputee himself fairly constant. Here it is necessary to obtain certain "base line data" from which to infer the relative contributions of the suction socket and the new prosthesis. Our base line data consist of the average level of performance of the amputee on his old prosthesis, as measured by his skill in walking, his achievement test ratings, and certain force plate data which give an objective index of the pattern of his gait and the ground reactions thereto.

After the subject has learned how to use his suction socket in combination with the old prosthetic device, similar data are collected. Finally, after the new prosthesis being studied has been attached to the suction socket and he has learned to use it, the amputee is subjected to the same testing procedures, and comparable data emerge. By a process of interpretation, it now becomes possible to estimate with a reasonably high order of probability how much of the performance level is due to the suction socket, how much to the prosthesis being tested, and how much to the new prosthetic device in combination with the suction socket. One suspects that such a procedure minimizes the role of factors which are extrinsic to the experimental situation, but it by no means eliminates them.

The importance of the team approach to biomechanical issues and problems in the service testing of artificial limbs is clearly evident to us. So also, I think, are some of its limitations and difficulties. From the very beginning, we have sought to develop a maximum cross-fertilization of ideas from all relevant professional areas. An important practical problem immediately arises. What professional groups can be expected to make a maximum contribution to the service testing program? I should say that there is no ready answer in this matter. In the particular problems which we have been facing, we have developed a biomechanical team consisting of an orthopedic surgeon, an anatomist, a physiotherapist, a limb-fitter, several engineers, a number of prosthetic technicians, and several clinical psychologists. On the whole, this human engineering group has achieved fruitful collaboration.

However, I should not like to minimize some of the real, practical problems which members of such a biomechanical team face in their day-to-day relationships with each other. As a member of the team, I can speak of the difficulties with some degree of understanding. First and foremost, perhaps, is the matter of duties and responsibilities which the various professionals must assume. Here one finds oneself concerned more with professional prerogatives than with the realistic demands of the research program itself. It was only after many weeks of clarification, involving long periods when some of the professional members of the group were often quite disaffected, that a *modus operandi* finally began slowly to emerge.

The final arrangement represented a compromise between what each professional preferred to do and what the realistic situation required.

I believe that we have solved many of our problems, but I should like to venture the opinion that, in human engineering research of the kind we have been conducting, others will find that many of the same kind of problems will continue to plague them. This is not difficult to understand against the background of our own experience. For example, in the practical day-to-day operations of the research program, each professional must be prepared, within the limits of his knowledge and skills, to function in a professional area other than his own. Thus, the orthopedic surgeon frequently has to play the role of the clinical psychologist who, in turn, may have to function as a physiotherapist and offer training to the subjects. Such a situation demands enormous flexibility of team members and makes it mandatory that they be prepared, at least to a limited extent, to cross professional lines in the prosecution of the research plan. One need not add, I think, that this is seldom achieved with smoothness. In our experience, most professionals tend to feel basically secure only within the confines of their own discipline, and it is easy for interpersonal relations to deteriorate, with great loss to the research, when professionals are required to function in circumstances which involve fluid professional lines.

When an experimental plan has been adopted and put on paper, it is, of course, essential for all those participating in the research to adhere rigidly to it until such time as it may be changed by general agreement. Our experience has been that it is unusually difficult for the members of our biomechanical team to live up to this principle in actual practice. Instead, each professional has had a strong tendency to make changes, some minor, some major, in the procedures of the experiment to square with his own particular professional prejudices. I need not draw the reader's attention to the fact that such departures from the experimental design are dangerous and may, indeed, be fatal to the research. We have had constantly to fight them. Perhaps wise statesmanship is all that is required, but I am becoming increasingly convinced that only through the mutual give and take of conference can such issues be resolved, and then frequently only with great difficulty.

I may mention another related difficulty which may easily be overlooked. It rarely happens that the contributions of the several professional members of the human engineering team are of equal importance, variety, or extent. In cooperative research of the kind we are discussing, however, it is essential to have all professionals equal in fact as well as in principle, and yet to accord to each an amount of consideration justified only by his actual contribution to the progress of the research. In actual practice, we have found this enormously difficult to do.

Perhaps the greatest difficulty, however, in the kind of cooperative biomechanical research described in this paper, is the difference in professional background, outlook, and aspirations of the professional members of the human engineering team. It is much more than a terminological and semantic series of problems which must be constantly met. Persons who sim-

ply do not have a basically experimental approach to problems must be sensitized to the possibilities of using the idiom of science as their mode of expression. This demands a continuing need for cross-education in each other's professional areas, a constant refocusing of one's perspective, and an unceasing demand to look at problems from the standpoint of a professional field different from one's own. If, as I believe, such learning for team members is inherently painful, one can begin to appreciate problems of this nature which must be faced.

One of the problems which we are only beginning to face has to do with the evaluation of our many data and the preparation of reports on our findings. Many classes of data have emerged from our studies so far, and it is difficult to know how much importance to attach to certain of them. The easy answer, I suppose, is to express more faith in those data which have been derived from so-called "objective" procedures; but one suspects that this might rob the research of much of its potential fruitfulness. In the final analysis, it is useful to recall, we need information not only about the prosthetic device whose efficiency and usefulness are being evaluated, but also about the subject's reactions to it, complaints about it, and suggestions for its improvement. An enormous number of really subtle facts intrude upon our consciousness.

We have developed a method for evaluating our data which, we have reason to believe, should prove useful and adequate to our needs. This procedure has not been completely formalized as yet, but the broad outlines are rather clear. It is our plan to have each of the several classes of data which have been collected by the various professionals subjected to careful scrutiny by the person responsible for obtaining them. This professional, utilizing such procedures as the psychologists can make available to him, will reduce his data to qualitative and quantitative statements or units which are comparable from one amputee subject to the other. The staff member's duty will be, in essence, to boil down his findings and make an interpretation of his data which will reveal group trends.

The conclusions which emerge from his findings and the interpretations which he makes of the latter will then be submitted to an Evaluation Committee. The committee will consist of an engineer, an anatomist, and a psychologist, plus a recorder, whose task is that of fitting the conclusions developed by the various professional groups into a coherent picture from which a supportable structure of warranted inferences may be erected. An obvious difficulty immediately suggests itself. How much weight should members of the Evaluation Committee attach to the several different kinds of data? I am of the persuasion that those charged with evaluation of the data derived from the service testing experiments and studies outlined above will have to reject the spurious distinction between qualitative and quantitative findings and will need to arrive at a rationale of interpretation which will do full justice to both classes of findings. This is likely to be easier in principle than it is in practice.

As our service testing studies are currently designed, we should expect to reach supportable conclusions in the following areas:

(1) Approximation of gait with the prosthetic device to normal (non-amputee) gait.

(2) Number and types of specific tasks which can be effectively accomplished with each of the prosthetic devices evaluated.

(3) Expressions of feeling, attitude, and opinion by the amputee concerning the utilization of each prosthesis and the psychological reactions to the device.

(4) The influence of various prostheses upon stump and body morphology.

(5) Information concerning fit, alignment, and maintenance problems inherent in the several prosthetic devices.

(6) Changes in habit patterns of amputees resulting from the use of different prostheses.

(7) Physical and psychological training useful in facilitating adjustment of the amputee to a prosthetic device.

(8) Personality characteristics of "good" and "poor" amputee walkers.

In addition to conclusions in these general areas, we should arrive at reliable information with respect to the mechanical assets and liabilities of the prosthetic devices studied which may be used as basis for making improvements in engineering design and fabrication.

In all, the program of service testing of prosthetic devices which we have undertaken offers a real series of challenges and responses. With the untiring devotion of all of the professional members of our human engineering team, we hope to meet each challenge with an appropriate response.

Summary

This paper has reviewed some of the psychological considerations which enter into the selection of amputee pilot wearers of prosthetic devices which are to be service tested. Some attention has been directed to issues and problems which arise in connection with experimental design in a human engineering problem of this kind. Consideration has been briefly given to difficulties which arise in connection with the development and utilization of a human engineering research team consisting of engineers, prosthetic technicians, psychologists, orthopedic surgeons, and other professional personnel. The paper has indicated some of the values and limitations of a cross-disciplinary approach to a typical biomechanical problem, and to the implications of team work with respect to human engineering research. Finally, several suggestions have been offered in connection with methods of interpreting data and the types of conclusions which may be expected to come from research of the type considered in this paper.

Reference

1948: Experimental Design for the Service Testing of Prosthetic Devices for Above-the-knee Amputees. Research Division Report. College of Engineering, New York University, New York.

A PRELIMINARY EXPERIMENT ON THE EFFECT OF DIAL GRADUATION AND DIAL SIZE ON THE SPEED AND ACCURACY OF DIAL READING

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This is a report of a preliminary experiment on the effect of dial size and dial graduation on the speed and accuracy of obtaining quantitative information from dial type instruments. The purpose of the experiment was to determine approximately the range within which the results of further and more complete studies might fall. These studies on factors influencing dial reading are being made at Princeton University under contract with the Aero Medical Laboratory, Wright Field.

Apparatus and Procedure. FIGURE 1 shows the apparatus as viewed from the subject's side. The subject sits in a three-sided enclosure, four feet square. He puts his head against a cushioned head-rest which keeps his eyes at a reading distance of twenty-eight inches from the test material. The single dial at eye height on the panel is a sample dial. This dial, like all the sample dials used, has no pointer. The particular sample which is presented in the panel aperture before each trial indicates to the subject the kind of dial which he will have to read on the next test card. When the subject is ready, the experimenter slides the test card into position and illuminates it. Every test card has twelve dials of identical design which the subject reads row by row, from left to right. Actually, the subject never sees the sample dial and the test dials at the same time, as might be assumed from the figure. Two small projectors, not shown in the picture, are used to illuminate the sample dial and the test card independently.

On the experimenter's side of the apparatus, there is (1) a supply bin containing test cards, (2) a slide mechanism for moving the test cards into position before the subject, (3) a second slide for presenting the sample dials, (4) a pair of stop clocks for timing the subject's performance, and (5) a storage bin into which test cards are placed as they are used.

The experimenter inserts a test card in the sliding panel and moves it into place in front of the subject. Next, he throws a control switch to change from sample dial illumination to test card illumination. This starts the two stop clocks. The subject begins reading immediately. As the first reading is called out, the experimenter stops the first clock. At the eleventh reading, the second clock is turned off. Illumination goes back to the sample dial after the twelfth reading. Although the subject makes twelve readings on every card, the experimental analysis is based only upon his readings of the central set of ten dials on each card.

Stimulus Materials. Eight dial designs were used in the experiment. These designs are shown in FIGURE 2. There were 100's dials (*i.e.*, dials reading from 0 to 100), 200's dials, 400's dials, and 600's dials. For each scale length, there were dials graduated by fives, shown in the top row, and others graduated by tens, shown in the lower row. Further, for each type

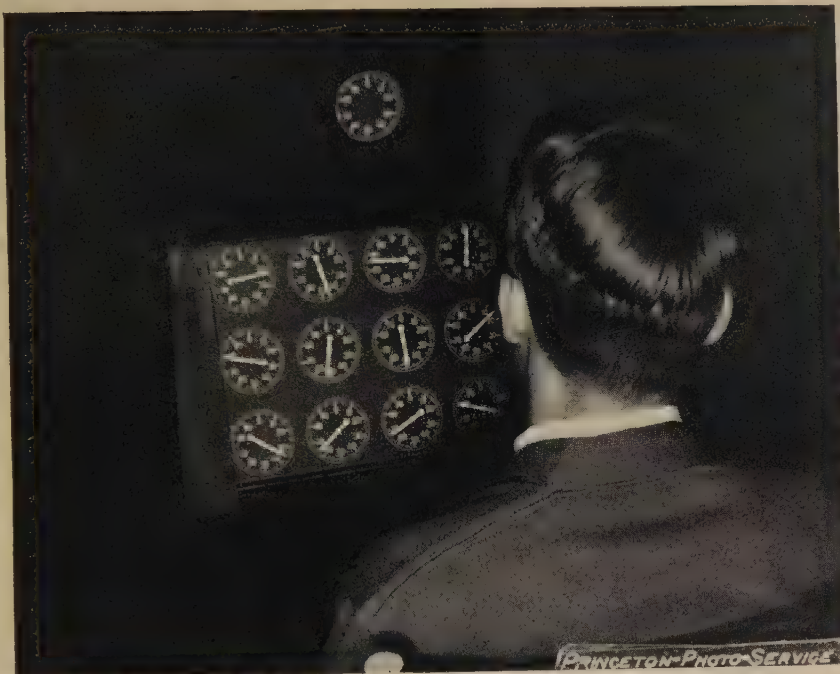

FIGURE 1. Photograph of the test situation. The test dials shown are 2.8 inches in diameter.

FIGURE 2. Types of dials studied.

of dial, two sizes were used: one was 2.8 inches in diameter, the other, 1.4 inches in diameter. For each type and size of dial, three test cards were available. Thus, there were 48 cards in all.

The stimulus materials were photographs printed on mat paper with as high degree of contrast as could be obtained. The illumination was such

that the white parts of the dials were at a brightness of 6 foot lamberts. The black areas were at a level of about 0.6 foot lamberts.

All the dial photographs used in the experiment showed the pointer within three tenths of a unit of some exact unit position on the scale. Settings were kept within this precision in order to eliminate ambiguous settings midway between two unit positions. The precision of each setting was checked by projecting the photograph negatives to a twenty-inch diameter size.

Plan of the Experiment. Each subject read 30 dials of each type and size. His instructions were to make each reading to the nearest unit. Since

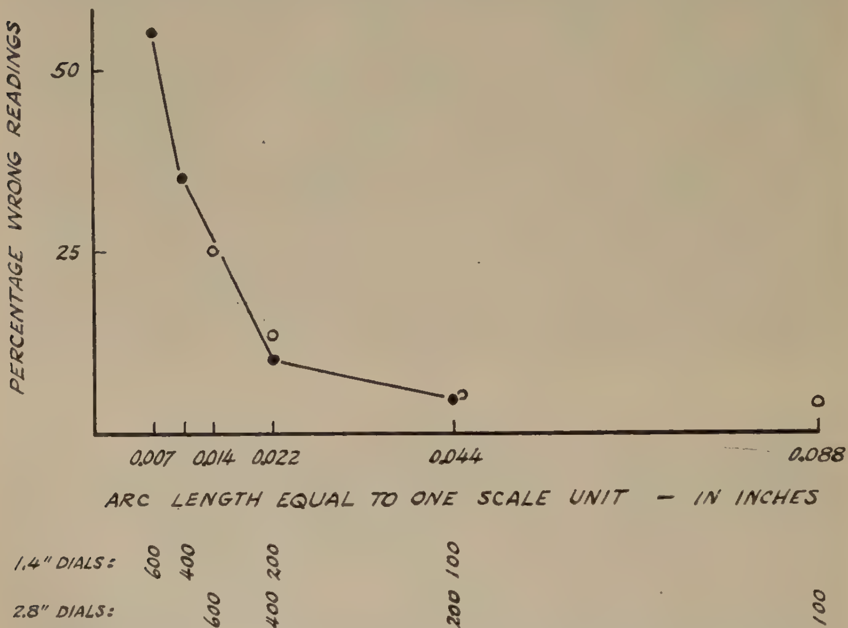

FIGURE 3. Frequency of reading errors for dials graduated by fives. Data for 6 subjects: 30 readings each per dial, under accuracy instructions.

readings were made to units, and not simply to the nearest division, interpolation to fifths or tenths of divisions was necessary. The subjects were instructed to be as accurate as possible in their readings, to read as carefully as they would when making slide rule calculations. Each subject read 24 of the 48 stimulus cards on the first experimental day and the remaining 24 on the second day. Six subjects, all graduate students in psychology, served in the experiment. The card sequences which were used introduced systematic rotations of the size and design variables. In order to minimize practice or other order effects for the group, the time of appearance of individual cards was counterbalanced for the different men.

Results. The results of the experiment are shown in FIGURES 3 to 5. Where differences were observed, they were orderly and large. For this reason, and because the experiment was conducted as a preliminary test

with a restricted amount of stimulus material, no statistical analyses have been made on the data.

FIGURE 3 shows the frequency of reading errors for the dials which were graduated by fives. Percentage of wrong readings is plotted as a function of the length of arc devoted to each scale unit. Any reading not given exactly to the nearest unit was scored as incorrect. Arc length is given in inches. Thus, as shown at the bottom of the figure, a 600's dial 1.4 inches in diameter has each unit on the scale represented by .007 inches. Clearly, a 200's dial of the 1.4 inch size and a 400's dial of the 2.8 inch size have the same arc length for one unit of the scale distance. The same is true for the small 100's dial as compared with the large 200's dial. The solid points plotted in the figure are for the small dials, the open points for the large

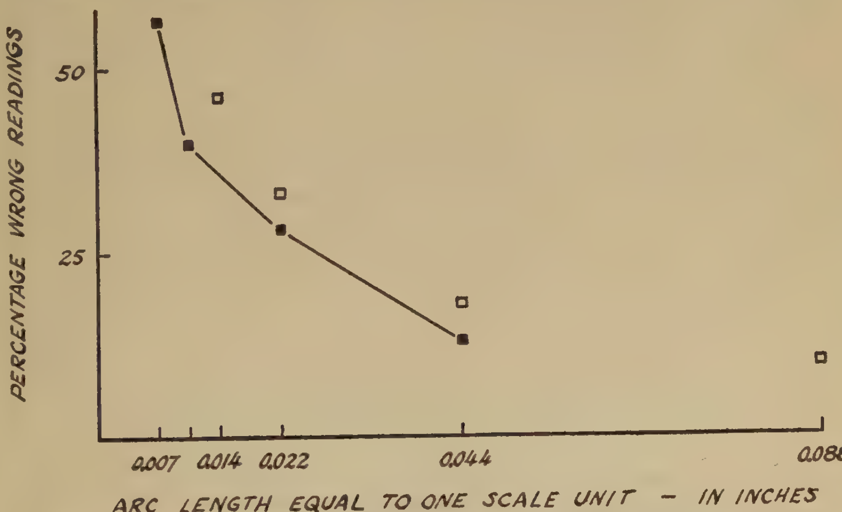

FIGURE 4. Frequency of reading errors for dials graduated by tens. Data for 6 subjects: 30 readings each per dial, under accuracy instructions.

dials. Points for the smaller dials are connected by straight lines and it is clear that the data for the large dials are fitted well by this curve for the smaller dials. Thus, error frequency for these dials graduated by fives was a function of linear arc length per unit and was independent of dial size. Increase in the number of errors was very rapid when arc length per unit became less than 0.02 inches. Over the range of scales tested, errors increased in frequency from a minimum of about 4 per cent to over 50 per cent.

FIGURE 4 shows the data for the series of dials which were graduated by tens. It will be noted that the frequency of errors for these dials was generally larger than for the dials graduated by fives. For the 400's and 600's dials of the smaller size, however, error frequency seemed to be about the same whether graduation was by fives or tens. For the dials graduated by tens, the data for the large dials (open points) and small dials (solid points) are not fitted so well by a single curve as they were in the case of the

dials graduated by fives. This suggests that the exact role of dial size warrants further study.

Note that FIGURES 3 and 4 indicate that error frequency approaches a minimum value when arc length per scale unit is 0.05 inches or somewhat longer. This value agrees very closely with that obtained by Williams and Grether in a previous study of dials graduated by tens.[1]

FIGURE 5 presents data for speed of reading. It summarizes the time measurements for all the readings which were made, for large and small dials and for dials graduated by fives and tens. In this figure, average read-

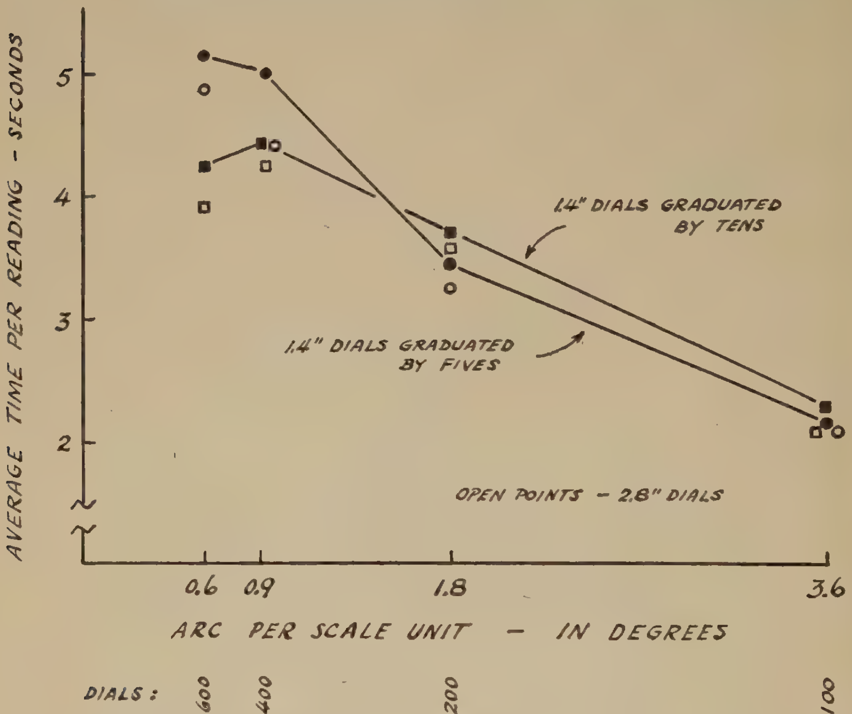

FIGURE 5. Reading times for all dials. Data for 6 subjects: 30 readings each per dial, under accuracy instructions.

ing time in seconds is plotted as a function of arc per scale unit, where the arc is measured in degrees. Small dials are again represented by solid points and large dials by open points. Points for the small dials are connected by straight lines. The data show that average reading time increased from two seconds to four or five seconds as the arc devoted to each scale unit decreased from 3.6 to 0.6 degrees. Dial size had a consistent but minor effect. Most significant is the fact that, within the range of dial sizes studied, reading speed was primarily a function of the number of degrees subtended by each scale unit, or, if you will, a function of scale complexity and numbering scheme which necessarily vary with the number of scale units represented on the dial circumference.

Summary

Results of a preliminary experiment involving six subjects, eight different dial designs, and two sizes of dials have been reported. Measures of reading time and error frequency were taken. The data obtained must be interpreted in the light of the fact that the subjects were graduate students reading at their own pace under instructions to be as accurate as possible. It was observed that frequency of dial reading errors was primarily a function of the arc length in inches devoted to one scale unit. For maximum reading accuracy, about 0.05 inches per scale unit seems to be required, although this distance may depend in part on whether the scale is graduated by fives or by tens. Regarding speed of reading, it was observed that speed depended most on the angular representation of each scale unit on the dial circumference. Reading speed was, therefore, relatively independent of dial size within the size limits studied, but varied markedly with the total number of units portrayed on the scale.

Reference

1. WILLIAMS, A. C., & W. F. GRETHER. 1947. Speed and accuracy of dial reading as a function of dial diameter and spacing of scale divisions. Army Air Forces, Air Materiel Command, Memorandum Report TSEAA-694-IE, March 31.

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